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The Tucson, Arizona, Flood of October 1983

Committee on Natural Disasters
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For:

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CONTENTS

INTRODUCTION

"The 100-year flood has come and gone, so, by all rights, Tucsonans should enjoy another century of great Southwest weather."

--postflood message sent to national media by Metropolitan Tucson Convention and Visitor's Bureau

"This is a desert?" asked an October 2, 1983, headline of the Arizona Daily Star above pictures of lateral erosion caused by desert streams with huge standing waves. The Santa Cruz River, which is generally dry 300 or more days per year, had only one of its 18 bridges open for service on the morning of Monday, October 3. Along the Rillito, a tributary of the Santa Cruz, hundreds of area residents watched on Sunday, October 2, as the river gradually eroded 100 ft from its bank through a parking lot and undermined an office building, which collapsed into the widened stream. The water from the combined streams overflowed its banks beyond the Tucson metropolitan area to flood acres of farmland and force the evacuation of the entire community of Marana, which was situated in the stream's delta. Early estimates of the costs of repairing public bridges and major roadways in the Tucson area ranged from $54 to $100 million.

The tropical weather pattern responsible for this flooding also caused major floods along the Gila River and two of its tributaries, the San Francisco River and the San Pedro River. A few days earlier another storm caused floods in Prescott, Arizona. Particularly hard-hit were Clifton (a mining community along the San Francisco River already beleaguered by a bitter labor strike), Marana and Rillito (downstream from Tucson along the Santa Cruz), and several communities along the Gila River from Winkelman to Kelvin (Federal Emergency Management Agency, 1983). So widespread and severe were the floods in Arizona south of the Mogollon Rim that some regard them as the worst disaster in Arizona since it became a state in 1912.

There are many aspects of the Arizona floods of October 1983 worthy of further investigation. Some examples are the sociological effects of the flood on the tension-ridden community of Clifton, where strikers accused the Governor of a greater readiness to use the National Guard to control the strikers than to deal with the flood emergency; the special problem of great distances hampering flood relief efforts in a state where the flooded communities were widely separated from each other and from the disaster assistance center in Phoenix; the almost total collapse of the road system in southern Arizona, where one bridge served as the last remaining link between Tucson and Phoenix; or the problems of places like Marana where desert rivers debouch beyond their deeply incised channels. We do not attempt to address all these potentially interesting topics but instead focus on metropolitan Tucson and on what we regard as the most unique aspects of the event: the flood behavior of desert streams, and the implications of recent rapid urban growth and development for dealing with the flood hazard.

Tucson provides an excellent site for studying the problems of rapid urban growth in the desert. It is one of several cities in the Sunbelt that have for the past four decades had a rate of growth well beyond the national average. The rapid growth in the Sunbelt is often attributed, as the name indicates, to the climatic amenities of the region. The long-sustained rapid growth has also attracted many people who are interested in the economic climate. Rapid growth creates many economic opportunities. This is especially true in places like Arizona, where the prevailing opinion is that the use of private land should be free from government interference. Newcomers see Arizona as a promising place to work under fewer of the planning constraints imposed in many other areas.

A perennial problem in this desert area of rapid growth stems from the newcomers' unfamiliarity with local environmental constraints. Images, ideas, and institutions from outside are applied, however inappropriate they may be. A prime example is floodplain zoning, in which many provisions were designed for streams in humid areas. On desert valley floors, true floodplains with overbank flows are rare while lateral erosion of arroyo banks is common (Committee on Natural Disasters, 1982). Basic understanding of such facts and of their implications for wise planning is not widespread among professional engineers or the general public. In part this stems from the current limits of scientific knowledge of desert streams; in part it is a natural result of the large influx of newcomers unaware of desert conditions; it also results from general attitudes that tend to favor growth rather than planning.

For all of the reasons just mentioned, Tucson provides an exciting locale for studying human adaptation to a desert site. Furthermore, a long, detailed, and continuous record of arroyo cutting on the Santa Cruz is available. This record documents past floods and the tremendous changes in the river's landscape since Tucson became part of the United States with the Gadsden Purchase of 1854.

In the remainder of this report we discuss the Tucson flood from the perspective of these themes. We try to answer the question of what happens during a major flood in a desert area that has undergone rapid urban growth. As we do so we try to point out scientific research questions or public policy issues that could be addressed by more detailed research. Chapter 2 discusses the meteorological event and the warning process, Chapter 3 discusses the geomorphology and hydrology of the Tucson Basin, Chapter 4 examines the human response to the flood, and Chapter 5 offers our conclusions.

THE METEOROLOGICAL EVENT AND THE WARNING PROCESS

Episodes of heavy rainfall over extensive parts of northwestern Mexico and the southwestern United States occur nearly every year in late summer and early fall. The location of areas receiving maximum precipitation from the storms varies from one storm period to the next and depends on the meteorological conditions prevailing at the time of the event. Storms that produce the largest amounts of precipitation occur when ocean temperatures in the southeastern part of the Pacific Ocean are high, when moist air associated with the remnants of a tropical cyclone in that region is drawn across Mexico into the American Southwest, and when this air then interacts with a significant frontal system associated with an upper-level cold trough or low over the region.

This "tropical connection" has been examined by a number of scientists, notably Douglas (1972), Pyke (1975), and Court (1980). They have identified the significant events in the precipitation history of the Southwest attributable to tropical storms. Their work has been analyzed and amplified by Hansen and Schwarz (1981), who have established the conditions under which a hypothetical storm would produce maximum concentrations of precipitation in Arizona. They suggest that the ideal conditions are:

1. Antecedent synoptic-scale weather features that permit the accumulation and transport of significant moisture into the Southwest well ahead of a tropical cyclone circulation. This moisture is necessary for the rainfall to be of long duration. The August 1951 storm that gave the greatest long-duration rainfall of record had such an antecedent weather feature. This feature allows for substantial rainfall prior to that associated with the hypothesized tropical cyclone circulation.

2. The southward development of a midlatitude cold trough aloft to help accelerate the storm as it turns northward or north-northeastward and crosses Baja California's coast and mountainous backbone at its lowest elevation (near 29°N latitude). The accelerated speed decreases the time the storm spends over land and therefore minimizes loss of intensity. In the optimum case the tropical cyclone should regain some of its intensity as it moves over the small area of warmer waters in the northern portion of the Gulf of California.

3. Maximum or near maximum sea surface temperature (SST) off the west coast of Baja California. This permits an offshore tropical cyclone to remain fully developed farther north than under normal SST conditions. This apparently was the case with the September 24-26, 1939, storm. Tropical storm Joanne in October 1972 was also fed by above-normal SST.

4. A well-formed tropical cyclone gaining intensity well south of Baja California and moving slowly northwest or northward so as to permit the optimum realization of the antecedent tropical cyclone rainfall.

5. A tropical cyclone track that, after reaching the latitude of Baja California, parallels the coast at just the right distance offshore so that, in addition to having a good supply of energy from Pacific Ocean waters, the outer fringes of the massive storm circulation draw from the very warm waters of the Gulf of California.

6. Entrance into southwestern Arizona with a circulation of great strength, after which the remnant storm interacts with a significant midlatitude frontal system associated with an extremely cold trough or low pressure aloft, as occurred in the disastrous storm of September 1970.

The list of conditions established by Hansen and Schwarz was derived by examining a large number of episodes of heavy rainfall that had tropical origins and were associated with the remnants of tropical storms that hit the American Southwest. Table 1 lists some of the most significant tropical cyclones that have produced moisture in the area.

THE STORM OF SEPTEMBER 28-OCTOBER 3, 1983

The August before the storm of September 28-October 3, 1983, had been a very wet month; so had September. In fact, it had rained almost every other day at many climatological stations in Arizona. This, in the normally dry fall season, was unusual. On September 28 the surface weather map exhibited few unusual features. A thermal low lay over the head of the Gulf of California, and the tail end of a weak cold front appeared across the Great Basin to the north. (Weather maps may be found in Appendix A.)

At the 500-mb level, however, an immense trough elongated in a southwesterly to northeasterly direction had developed, bringing tropical moisture into the area. At the same time, a tropical storm, Octave, was gaining strength off the tip of Baja California. Winds at virtually all levels above the surface were from the south to southwest. Isobars at the 500-mb level trended in the same direction. The National Weather Service (NWS) Forecast Office in Phoenix noted this and forecast the renewal of summer monsoon-type showery weather.

Precipitation in Tucson began innocently enough at 5:00 p.m. on Wednesday, September 28. Off and on until midnight, 0.07 in. of rain fell. The rain then ceased until noon on September 29, when a shower occurred. Rain then persisted until noon on September 30. The first flash flood warning of the period was issued by the Tucson NWS Office on September 29 for the period between 5:40 p.m. and 8:00 p.m. At 10:20

TABLE 1 Selected Storms that Have Affected the American Southwest

Date	Tropical Storm	Affected Area
Sept. 24-26, 1939	--	Arizona/California/Nevada
Aug. 26-29, 1951	Charlie	Northwest Mexico/California/Arizona
Aug. 17-19, 1960	Diana	Baja California/Sonora
Sept. 15-19, 1963	Katherine	Southern California
Sept. 23-26, 1965	Hazel	Northwest Mexico
Aug. 29-Sept. 2, 1967	Katrina	Southeast California/Southwest Arizona
Sept. 7-14, 1969	Glenda	Central Arizona
Sept. 4-6, 1970	Norma	Central Arizona
Aug. 27-Sept. 6, 1972	Hyacinth	Southern California/Arizona
Sept. 30-Oct. 6, 1972	Joanne	Southern, central, and eastern Arizona
Sept. 6-10, 1976	Kathleen	Southern California/Arizona
Aug. 11-15, 1977	Doreen	NW Mexico/California/Arizona
Oct. 6-11, 1977	Heather	Mexico/Arizona
Sept. 28-Oct. 3, 1983	Octave	Mexico/Arizona

p.m. a weather statement was issued indicating decreased rainfall and thunderstorm activity. Furthermore, it added:

> The Santa Cruz River is quite high--and persons living near the river should be cautious--as there may still be localized flooding of the lower banked areas. . . . Light to moderate rain is still falling over eastern Pima County--and dips and washes may still have some running water for the next few hours. Motorists in the affected areas should continue to use caution in eastern Pima County.

By Friday afternoon there were clues appearing that more heavy precipitation was due. Moisture, in the form of clouds, could be seen streaming northward from tropical storm Octave (Figure 1), and meteorologists at the Phoenix NWS Office marked the location of several embedded, precipitation-enhancing short waves rotating around the major upper-level trough (Figure 2). As a consequence, the hydrologists with the Joint Federal-State Flood Warning Office issued a statement:

> Heavy rainfall during the past few days has caused significant rises along many rivers and streams throughout the eastern two thirds of Arizona.
>
> Although no mainstream flooding has been reported, . . . the San Francisco River near Clifton remains near bankfull . . . and lowland overflow has been reported along the Santa Cruz River near Marana today. Significant flows have also been reported

FIGURE 1 Moisture from tropical storm Octave, located off the west coast of Baja California, may be observed in the band of clouds extending across northwest Mexico, Arizona, and New Mexico. This photograph was taken at 6:15 p.m. GMT on October 2, 1983.

> along portions of the Verde River and its tributaries and along Tonto Creek.
>
> The rains have saturated the ground and filled most streams and rivers. . . . Any additional rainfall will run off rather rapidly and could cause increased or renewed rises.

Thus, when it began raining shortly after midnight on Saturday, October 1, the Phoenix NWS Office issued a flash flood watch for all parts of central and southern Arizona and, in particular, south- and west-facing mountain slopes. It said:

> Many areas of central and southern Arizona have received from 2 to 4 inches or more of rainfall since Wednesday, September 28 . . . with lesser amounts elsewhere. The ground has now become

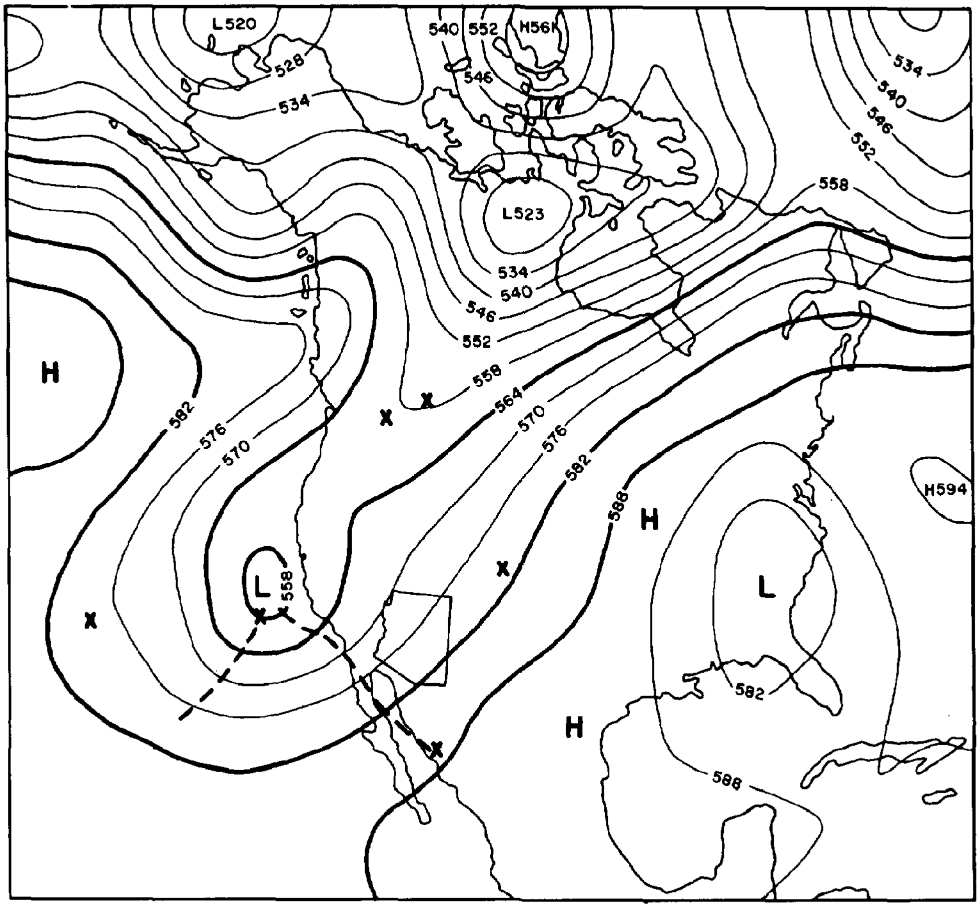

FIGURE 2 National Weather Service 500-mb analysis for Friday evening, September 30, 1983. Embedded short waves are shown by dashed lines.

saturated in a large portion of the state. As a result . . . additional rainfall in these areas now has a very high risk of running off almost immediately.

Satellite photos during the predawn hours show heavy amounts of moisture approaching Arizona from both the west and south. Very strong southwesterly winds in the upper atmosphere will cause this moist air to impinge upon the central mountains . . . and force the air to release its moisture. As a result . . . the potential for heavy rains exist for these south- and west-facing slopes of the central mountains . . . as well as those remaining portions of Arizona south and west of the central mountains.

Persons in the watch area, . . . particularly motorists and those in known flood-prone areas or in areas which have flooded recently, . . . should use extreme caution today. Check preparedness requirements and be ready to move to higher ground immediately if threatening clouds approach or if water levels in your area begin to rise.

Motorists should not attempt to cross flooded roadways . . . as water depths and currents are frequently misjudged.

The heaviest precipitation associated with the storm occurred shortly thereafter and was reported by personnel at the Tucson NWS Office. Their comments appear below:

> At 9:10 a.m. MST Tucson local radar is showing a heavy shower activity throughout eastern Pima, . . . northern Santa Cruz, and northwestern Cochise counties. Most of Pinal County is also affected. An inch and a quarter of rain has fallen at the airport here in Tucson in the last two hours and there have been numerous reports of one and a half inches or more throughout the city and outlying areas.
>
> All rivers, . . . washes, . . . dips, and other low-lying areas are reported running full. Motorists and persons in affected areas are advised to take extreme caution and not enter any flooded areas.

Heavy rains continued over much of Arizona during the morning. Rates of over 1/2 in./h were reported from a number of sites in the southeastern part of the state. By noon the Tucson NWS Office could report a lessening of precipitation, but flooding was widely reported in the metropolitan area.

The 2:50 p.m. statement from the Phoenix NWS Office on Saturday afternoon did not give much hope for relief. It read:

> [There is a] flash flood watch for south-central and southeast Arizona until 5 a.m. MST. . . . The watch area includes Pima, . . . Pinal, . . . Santa Cruz, . . . Cochise, . . . Maricopa, . . . Southern Yavapai, . . . Gila, . . . Graham, and Greenlee counties.
>
> A steady stream of subtropical moisture is moving into Arizona from the south. This will continue to bring numerous and locally heavy showers over all but the far west portions of the state. For tonight the areas most vulnerable to heavy rain are the central and east-central mountains southward.
>
> Heavy rains have continued to fall in the Tucson area through early afternoon. Satellite pictures indicate that much of Pima, . . . Pinal, and Graham counties are continuing to get heavy showers.
>
> A flash flood watch means flash flooding is possible. Motorists should stay out of flooded stream crossings and highway dips and avoid narrow . . . steep-walled canyons.
>
> Heavy rains of the past few days and again today have already brought considerable flooding problems. All persons with property subject to flash flooding should take immediate action for protection if possible.

During Saturday evening, continued runoff and the possibility of additional precipitation brought this flood statement from the Joint Federal-State Flood Warning Office:

> Continuing rains during the past several days and especially today have caused significant rises throughout the Santa Cruz Basin and its tributaries. Water levels throughout the river are extremely high with lowland overflows occurring in the Continental and Marana areas.
>
> Riverbottom road crossings throughout the Tucson area are closed because of the high water. Possible additional rains could cause further increases in river level or renewed rises with some additional overflow.
>
> Persons located near the river should remain alert to current conditions and the possibility of the sudden increases in river levels through Sunday.

The air flowing across Arizona continued to be warm and unstable, and satellite pictures and radar echoes continued to show large thunderstorms over northwestern Mexico. At 9:50 p.m. local radar showed mostly light showers in the Tucson metropolitan area moving toward the northeast. However, at 1:25 a.m. on October 2 the radar picked up a line of showers that extended from Redrock, north of Tucson, to a point just west of Sasabe. These cloud cells were moving toward Tucson at about 20 mph and were forecast to reach the area around 3:00 a.m. Satellite photographs had shown them to be increasing in intensity.

> Local inflow from very heavy and persistent showers and thunderstorms in the Tucson area has also dramatically increased the flow in the Santa Cruz River. The flow in the river has increased between Continental and Tucson. This flow is still far short of that which is needed to cause the river to leave its channel at Tucson. However, . . . local inflow into the Santa Cruz in the Tucson area from these heavy showers and thunder-storms has caused a sharp rise in the river. While the river is still well within its channel, . . . heavy lateral erosion of the river banks has . . . and will continue to take place through at least 9 a.m. this Sunday morning. Those persons affected by this erosion should move to a place of safety immediately.

At the same time, numerous law enforcement agencies were indicating that all dips, washes, rivers, and low-lying areas in the Tucson metropolitan area were full of water. The Rillito at North Country Club Road was overflowing its banks, and there was water in the surrounding streets. Considerable lowland flooding had occurred near Marana and northward along the Santa Cruz. The overflow of the Santa Cruz at Continental continued.

However, the worst of the heavy precipitation was over. Sporadic showers continued in the Tucson area through noon on October 3.

However, continued runoff on major watersheds contributed to severe flooding at Clifton on the San Francisco River, at Safford and Duncan on the Gila River, and on the San Pedro and Santa Cruz rivers. Most of these streams crested before noon on the third, but additional precipitation could have caused additional problems.

By 6:30 p.m. on October 3, showers and thunderstorms in the affected area had decreased markedly. The Phoenix NWS Office issued a flash flood statement that canceled the flash flood watch still in effect. The storm was over--the task of recovery had begun.

WAS THIS "THE STORM OF THE CENTURY"?

Suggestions that Tucson has seen its 100-year storm and need not worry about another one for another century are simplistic and false. Even if it were a 100-year storm, there would still be a one percent chance of another next year or any other year. A review of the probable maximum precipitation (PMP) conditions given above reveals that one ingredient in the maximum storm event was missing. Tropical hurricane Octave, like Norma in 1970, expired quietly at sea and did not penetrate Arizona. However, the copious and continuous precipitation associated with this particular event may be attributed to the presence of the other factors listed in the first part of this section. Ocean temperatures off the west coast of Mexico were above normal (Figure 3), and an elongated upper-level trough that penetrated to the tropics brought warm, moist, unstable air into the region. Also, cold air had been advected into the region on the back side of the trough.

The significant and unusual features of this storm period were the amounts of precipitation that occurred prior to September 28 and the duration of the precipitation in the five days that followed. August and September had been extremely wet over much of the central and eastern part of the state. September was the wettest September of record at a number of locations in Arizona. Then, once it began to rain on September 28, there were only brief respites from precipitation in the days that followed. At the Tucson NWS Office there were 26 different hourly observations in which precipitation was reported on September 28, 29, and 30. After the rain began again between 1:00 and 2:00 a.m. on October 1, it lasted for almost 42 hours with brief pauses between showers (Figure 4). Most of the severe flooding was associated with the persistent rains in the morning hours of October 1 and October 2. But, in comparison to precipitation from a large August thunderstorm, the amounts were small (Table 2), and the return periods for time durations of less than three hours were three years or less (Figure 5).

However, the rain that began falling shortly after 6:00 a.m. in western Tucson on October 1 culminated in a heavy shower of 0.78 in. between 3:00 a.m. and 4:00 a.m. on October 2, bringing a 24-hour total of 3.58 in. Values derived by Paul Kangieser, former State Climatologist for the National Weather Service, from the Precipitation-Frequency Atlas of the Western United States (National Weather Service, 1973),

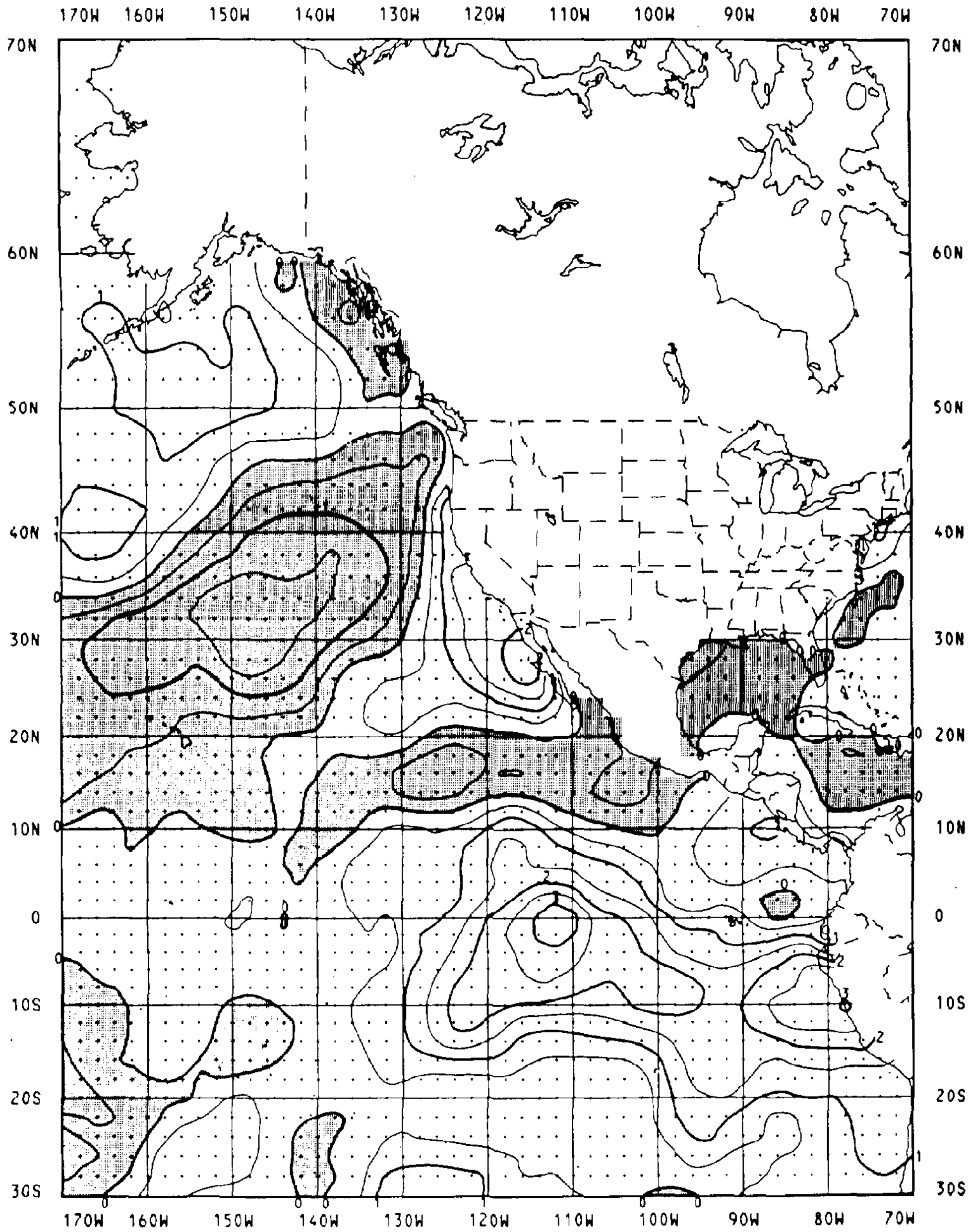

FIGURE 3 Mean sea surface temperature anomalies for September 1983. Note the pool of warm ocean water off the coast of Baja California where tropical storm Octave formed. The monthly anomaly is the difference between the monthly mean sea surface temperature and the climatological monthly mean value. Shading shows where the monthly mean is colder than climatology. The contour line interval is 0.5°. Source: Oceanographic Monthly Summary, 1983.

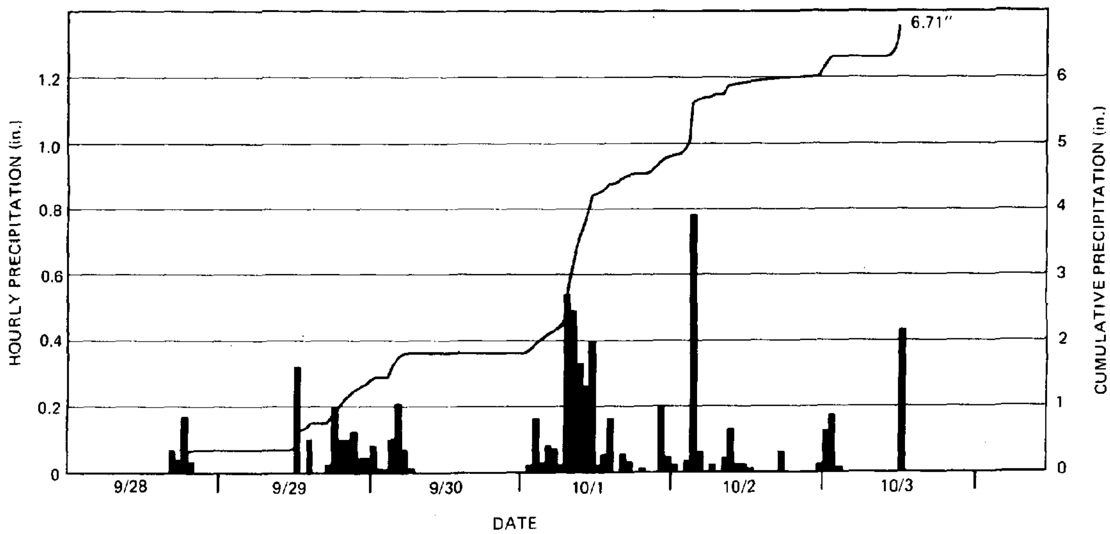

FIGURE 4 Precipitation at the Tucson NWS Office between September 28 and October 3, 1983. Bars show hourly totals; the solid line shows cumulative totals.

TABLE 2 Maximum Precipitation at Tucson from the Storm of September 28-October 3, 1983

Period	Precipitation (in.)	Date at End	Time at End
5 min	0.27	Oct. 2	3:20 a.m.
10 min	0.40	Oct. 2	3:22 a.m.
15 min	0.42	Oct. 2	3:22 a.m.
20 min	0.44	Oct. 2	3:22 a.m.
30 min	0.65	Oct. 2	3:22 a.m.
45 min	0.69	Oct. 2	3:22 a.m.
60 min	0.77	Oct. 2	4:01 a.m.
80 min	0.83	Oct. 2	4:16 a.m.
100 min	0.99	Oct. 1	8:55 a.m.
120 min	1.23	Oct. 1	9:15 a.m.
150 min	1.32	Oct. 1	9:45 a.m.
180 min	1.37	Oct. 1	10:15 a.m.
6 h	2.04	Oct. 1	12:00 p.m.
12 h	2.45	Oct. 1	3:00 p.m.
29 h	3.58	Oct. 2	4:00 a.m.

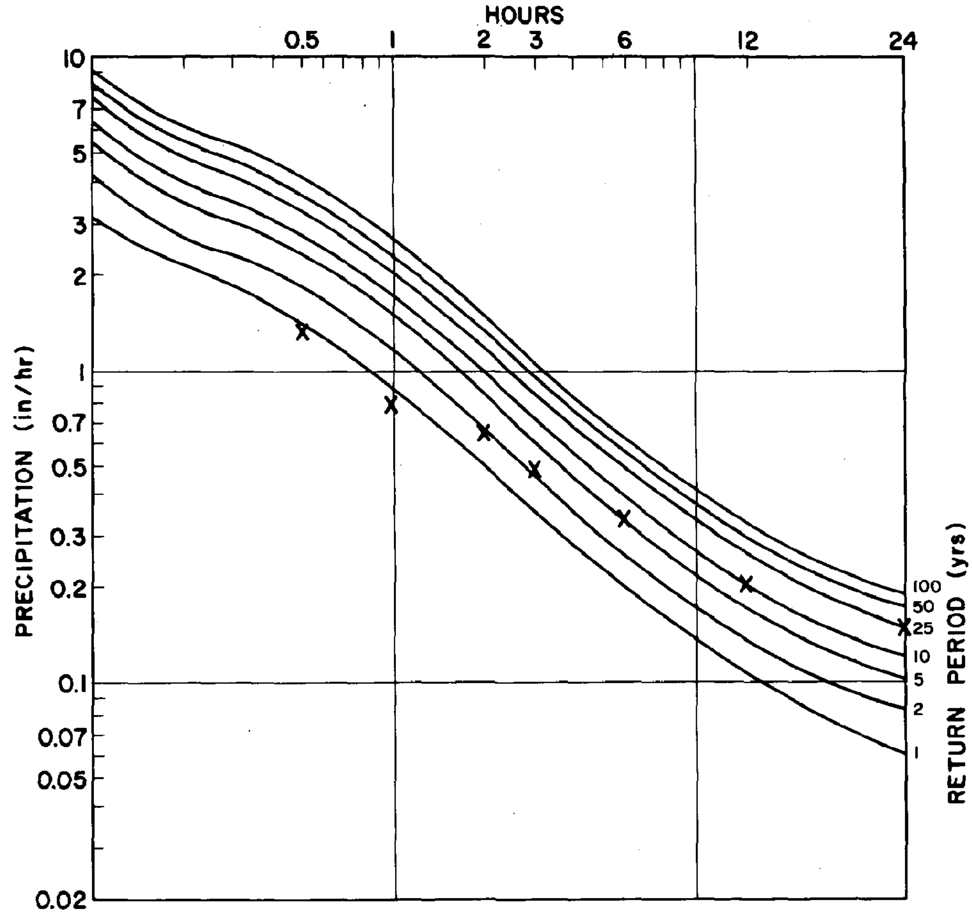

FIGURE 5 Rainfall intensity-frequency distributions at the Tucson NWS Office.

appear as Table 3. It can be seen from the table that precipitation occurring during the period of greatest intensity did not exceed values for a 25-year return period at the weather station located at Tucson International Airport.

There have been a number of differences of opinion as to the intensity of this storm. If one adopts techniques other than those used by Kangieser, including the Pearson III distribution, a return period of nearly 50 years can be derived. However, Kangieser argues that the Pearson III distribution overestimates return periods for rainfall durations longer than 6 hours. A more accurate estimate, he contends, can be made using smoothed regional values of the kind found in the Precipitation-Frequency Atlas of the Western United States (P. Kangieser, personal communication, 1983). Figure 6 compares return periods calculated on the basis of these two techniques.

TABLE 3 Estimated Return Periods for Precipitation in Tucson

Duration	Return Period (yr) 1	2	5	10	25	50	100
5 min	0.27	0.34	0.44	0.50	0.61	0.68	0.77
10 min	0.41	0.52	0.68	0.78	0.94	1.06	1.19
15 min	0.53	0.66	0.86	0.99	1.19	1.34	1.50
30 min	0.73	0.92	1.19	1.37	1.65	1.86	2.09
1 h	0.92	1.16	1.50	1.73	2.09	2.35	2.64
2 h	0.95	1.28	1.67	1.94	2.35	2.64	2.96
3 h	1.06	1.35	1.78	2.08	2.52	2.84	3.18
6 h	1.17	1.50	2.00	2.34	2.84	3.21	3.59
12 h	1.26	1.65	2.24	2.62	3.19	3.62	4.06
24 h	1.37	1.81	2.48	2.92	3.55	4.05	4.54

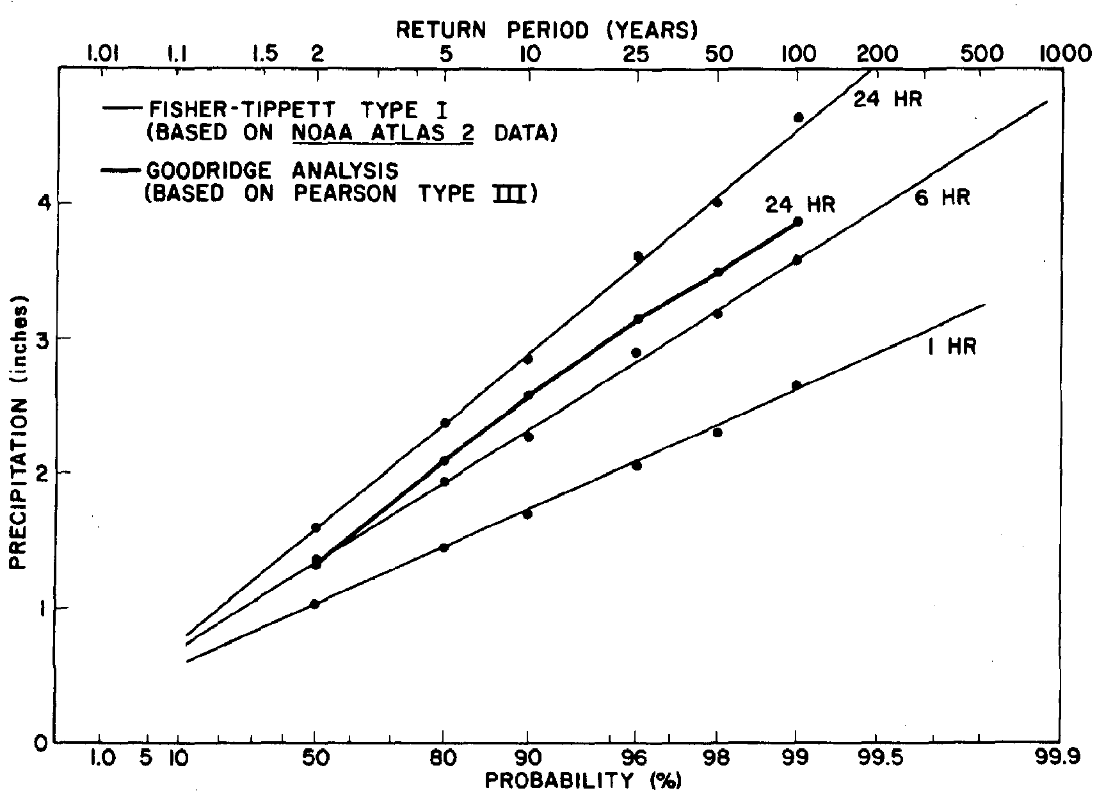

FIGURE 6 Return periods calculated on the basis of a Pearson III distribution and data from the Precipitation-Frequency Atlas of the Western United States (NOAA Atlas 2).

But how unusual was the meteorological event itself? On September 23, just prior to this episode in Sonora and eastern Arizona, the area around Prescott in central Arizona was drenched with rainfall from a tropical air mass. Shortly after October 3 another tropical storm entered the coast of western Mexico, and moisture from the storm contributed to flooding in Mexico and Texas. Some of the other periods when surges of tropical air from the eastern Pacific Ocean affected northwestern Mexico and the southwestern United States were listed in Table 1.

One of the largest and most severe storms with a tropical connection was the Labor Day Storm of 1970, which is generally used as a model of what can happen in Arizona. The isohyetal map for this storm appears in Figure 7. As can be seen, the areal extent of this storm and the amounts of precipitation dropped on the state were comparable to the present event. Intensities during the 1970 storm were higher, and the meteorological conditions were somewhat different, but the results were similar, although the area affected was farther north and west.

However, not too many of these persistent tropical surges have passed over the Tucson area and into the White Mountain region to the northeast. In this case, the flow of air at all levels directed a stream of moisture from off the coast of Baja California toward the northeast. It was the persistence of this flow that was unusual and not the intensity of the precipitation associated with any particular part of it. Much of the precipitation was orographic in nature. Maximum amounts occurred on the south and west slopes of the mountains, and the highest values were recorded at high elevations. Mount Lemmon reported over 10 in.; Blue, farther northeast, in the White Mountains, nearly 11 in. The location of the stream of moist air can be seen by looking at the map of total storm precipitation (Figure 8) and by examining the 500-mb charts in Appendix A.

Thus, although Tucson did not experience its "storm of the century" during September and October of 1983, it is possible that a future surge of tropical moisture across this area will cause such an event for the Tucson metropolitan region. Given the consequences of the 1983 storm, the result will be devastating.

THE WARNING PROCESS

The process of providing the public with timely warnings of impending weather-related disasters involves a number of groups that need to work in unity at the time of the event. To do so effectively requires working and planning together prior to the event. Lack of an adequate observational network, lack of adequate communication facilities, limited cooperation among agencies charged with serving the public, and a lack of understanding among governmental officials about the nature of disasters and about the available warning systems often result in a poor set of responses when an emergency situation exists. The situation in Pima County in early October 1983 was no exception.

During any major flood event, hydrologists and meteorologists need timely reports of precipitation and runoff. During the Tucson flood the

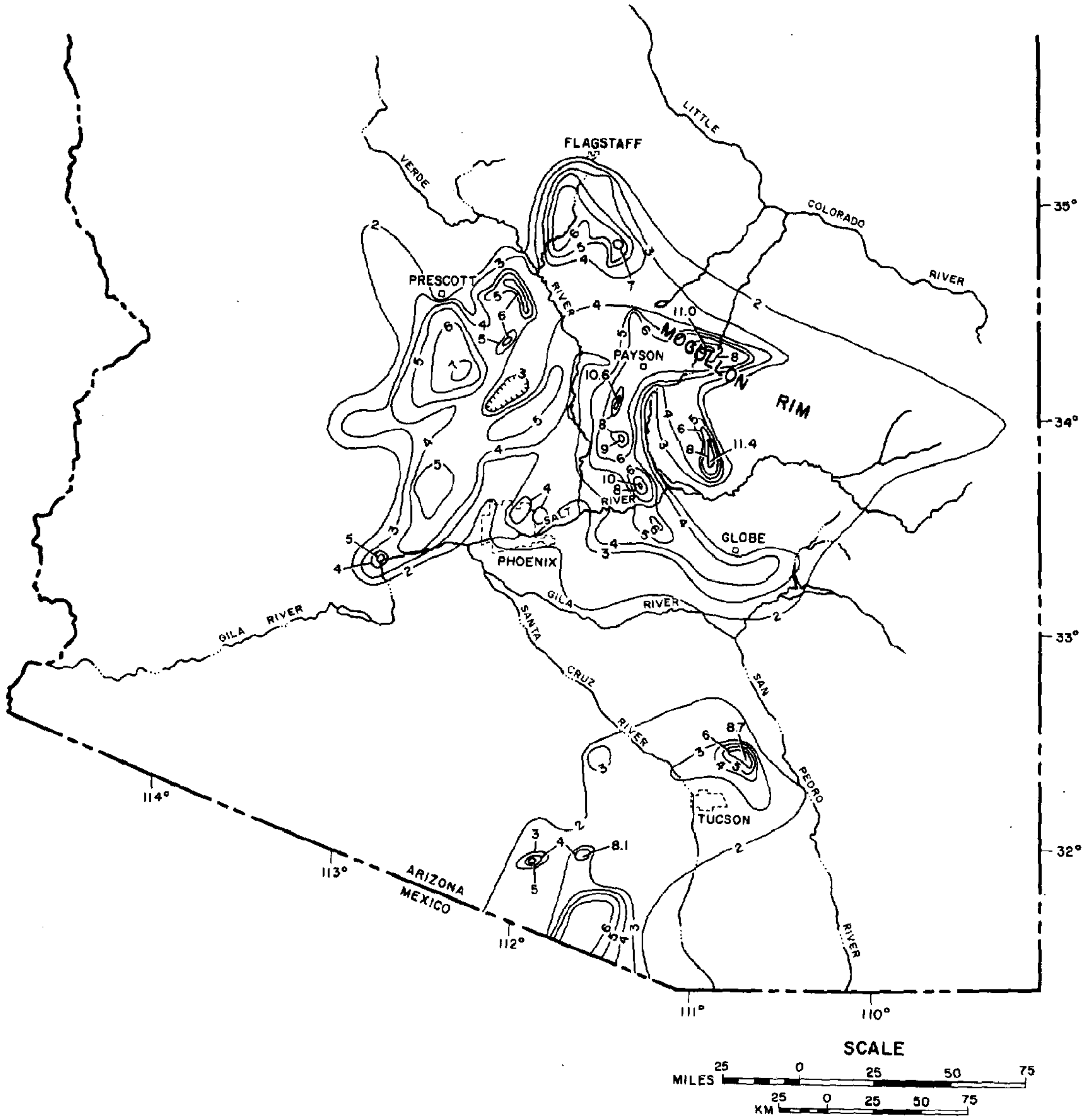

FIGURE 7 Rainfall in southern and central Arizona from the Labor Day Storm of September 4-6, 1970, in inches.

DARDC (Device for Automatic Remote Data Collection) Network of rainfall reporting stations worked reasonably well when queried locally by the Phoenix NWS Office's NOVA 4 computer. However, reports from the same network, when queried by the national Central Area DARDC Automated System (CADAS) failed to respond. Thus the only other precipitation data available to weather forecasters and hydrologists during the storm period were the routine morning and late afternoon reports from regularly reporting climatological substations and other agencies. Collection of reports from these stations and others was hampered in some

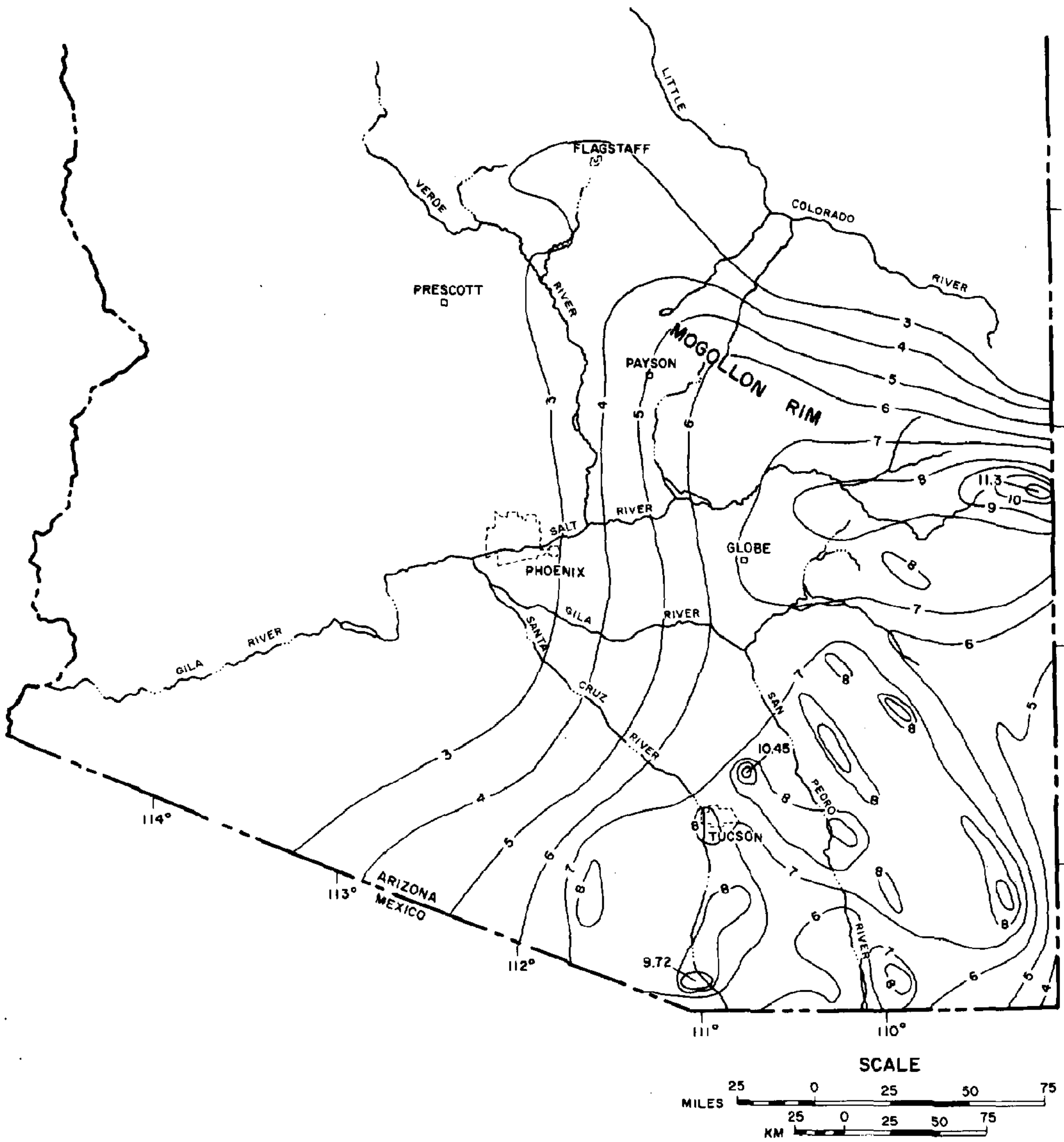

FIGURE 8 Rainfall in Arizona from the storm of September 28-October 3, 1983, in inches.

instances by telephone outages. However, in Tucson the local network of cooperating observers provided valuable information to the Tucson NWS Office.

The system to acquire real-time hydrologic data did not function effectively during the storm period. All stations in the network report at 00Z and every three hours thereafter via satellite to the downlinks at NOAA's Wallops Island facility in Virginia and at the Salt River Project office in Phoenix. Additionally, the stations report every 15 minutes to the Salt River Project after certain specific criteria are met. During the critical period of the storm on October 1, the Salt River Project downlink was out of service from 7:00 a.m. to about 8:30 p.m. due to computer problems. Valuable data were lost and not available to hydrologists concerned with problems of river flooding.

In addition to problems of acquiring data and information on precipitation and flood flows, there existed problems of communication and understanding. In evaluating their performance during the emergency, officials of Pima County admitted that their efforts could not be given superior grades but blamed part of the problem on inconsistent statements from the National Weather Service. As can be seen from the excerpts in the preceding text, this "passing of blame" was unjustified. From 6:00 p.m. on September 29 until midnight on October 5, the Tucson NWS Office issued 20 warnings and statements, of which 13 were radar-generated updates. In the same period the Phoenix NWS Office issued 28 warnings, watches, and statements, of which nine were flood warnings generated by the Joint Federal-State Flood Warning Office.

Weather statements and radar updates reflect observed conditions and vary with those conditions. Watches and warnings are subjective evaluations of meteorologic and hydrologic conditions occurring during the event. The consistency of such issuances depends on the available data and on the timing of their release. Use of weather watches and warnings by the public and by public officials requires that they understand them and that they understand reasons for what seem to be inconsistent statements and warnings.

All statements and forecasts of the National Weather Service are transmitted to users by the NOAA Weather Wire and by NAWAS (the National Warning System). The former is a statewide hardcopy teletype system to users. At the time of the Tucson storm, it included only three of five TV stations and none of the radio stations in the Tucson area. However, the Weather Wire was relayed to the two Tucson newspapers (the Tucson Citizen and the Arizona Daily Star) by the press-wire facilities of the Phoenix offices of the Associated Press and United Press International (incidentally, these organizations relay such issuances to subscribers of their radio services). The NAWAS voice transmissions went to all sheriffs' offices and other public safety agencies in the state. Thus the amount of information transmitted appears to have been sufficient for the public and the officials appointed and elected to care for their safety to have been well aware of the scope and extent of the disaster.

There is a national program to provide warning of impending disasters--the Emergency Broadcast System (EBS). However, activating this system was not possible because no primary EBS station had been designated in the Tucson metropolitan area and the only radio station that had volunteered to fill this gap was not on the Weather Wire and so did not receive EBS activation requests. Although several flood warnings from the Phoenix NWS Office were headlined EBS REQUESTED, they were not implemented. The Pima County Emergency Services Director was quoted in Tucson's Arizona Daily Star of October 12, 1983, as saying, "We just didn't see the need for activating the EBS system."

NOAA Weather Radio provided the best source of information about the progress of the storm to the agencies in the Tucson area that used it to monitor the weather conditions affecting their operations. According to Dave Williams in Tucson's Arizona Daily Star of October 7, 1983, "On Saturday, the best electronic sources of information about the flooding were the NOAA weather broadcasts."

Although the forecasts issued by the National Weather Service in Tucson during this storm episode were accurate and timely, problems did occur within the agency. Once the storm was in progress, many of the systems and networks used to measure precipitation and runoff malfunctioned, making it impossible to have a clear picture of the series of events that occurred during the storm. In addition, it is difficult for a National Weather Service Office such as that at Tucson, which had only one or two individuals answering the phones, making observations, and handling other station duties, to respond to all of the demands placed on it during an emergency period. Reasons for this are not entirely clear, but some of the problems clearly relate to a lack of manpower.

In addition, there evidently were no policies on the retention and analysis of data during and after the storm. In the past it has been customary for both the Corps of Engineers and the National Weather Service to investigate weather events of this magnitude. Only the Bureau of Reclamation Flood Office out of the Denver Federal Center was critically interested and involved in meteorological analysis of this storm episode.

As the events associated with this storm and flood show, the responsibility for particular kinds of analysis of events during and after weather-related disasters needs to be clearly defined. Lack of understanding of interagency responsibilities is a continuing problem. For example, at 4:30 p.m. on Monday, October 3, the Phoenix NWS Office stated, "The [San Carlos] reservoir is expected to begin spilling later Tuesday afternoon." In fact, spilling began about 1:30 p.m. that Tuesday. However, officials of the Arizona State Division of Emergency Services said in a press release issued Monday evening that they expected San Carlos to spill about midnight that night based on estimates of the State Department of Water Resources. When questioned about this difference of opinion, State Emergency Services personnel said that because people would have to be evacuated, they preferred to take the sooner rather than the later time--a difference of about 18 hours!

It would seem that these two forecasts (the former official and the latter not official) did not lend credence to public releases.

RECOMMENDATIONS

Additional efforts are needed to coordinate the work of the various agencies involved with disasters before, during, and after the events. Both state and federal agencies charged with coordinating the acquisition and analysis of meteorological and hydrological data must exert stronger leadership to ensure cooperation of all existing agencies within the affected areas. Some other topics that need attention are listed below.

1. Safeguarding Flood Data and Information

If the Federal Emergency Management Agency is to continue to be the lead agency in disaster mitigation efforts, there needs to be a clearer statement of the duties and responsibilities of NWS personnel during and after severe weather events so that the National Weather Service's contribution to the analysis of events can be clearly defined. During an event, efforts should be made to acquire and retain all data and information essential to understanding and analyzing it. These materials should be retained until needed by hazard investigators. The originals could be kept by the cognizant NWS office for a specified period of time, such as five years, after which they should be appropriately archived.

2. Investigation of Meteorological Conditions

Each major severe meteorological event should be investigated thoroughly by the cognizant local forecast office of the National Weather Service. These investigators should be assisted by such additional experts as are needed from the regional forecast offices. This analysis should be the basis for reports used by other local and federal agencies. It is an inefficient use of tax dollars to have each event handled on an ad hoc basis, with many federal agencies conducting an analysis of the meteorological conditions contributing to a natural disaster.

3. Issuance of Disaster Warnings

If the disaster or potential disaster is related to weather, then the National Weather Service should have sole responsibility for issuance of watches, warnings, and statements about existing and expected conditions to the public. This is true even in gray areas such as the collapse of dams weakened by rains or overtopping of dams because of excessive river flow.

4. Acquisition of Meteorological Data During Events

Local offices of the National Weather Service should encourage cooperative observers to report more faithfully on weather conditions during severe storm events. Also, ways need to be found to ensure redundancy in automatic systems so that data can be obtained under inclement weather conditions.

5. Communication of Warnings to the Public

Although NOAA Weather Radio appeared to operate effectively during the Tucson flood episode, too few people are aware of this service. During severe weather episodes it is essential that all electronic media make full use of all available information. Local radio stations could, for example, retransmit NOAA Weather Radio broadcasts. Additionally, local television stations, staffed with professional meteorologists, could rebroadcast NWS radar pictures and explain them to the public at the same time that they are presenting verbatim the latest NWS advisories on the air.

6. The Tropical Connection

Episodes of extensive, heavy precipitation have their origins south of the U.S.-Mexico border. To give American citizens adequate warning of these events, better cooperative programs should be developed with the states of northwestern Mexico to monitor and record weather events. Two specific suggestions are (1) the extension of the Automatic Hydrologic Observation System (AHOS) managed by the U.S. Geological Survey and (2) the establishment of a cooperative surface observation program with the state of Sonora or the government of Mexico so that severe storms may be monitored on their way across Sonora.

7. Cooperation Among Local, State, and Federal Agencies

During a major weather-related disaster, officials charged with public safety and emergency services should have coordination representatives of their agencies at the local offices of the National Weather Service. These representatives should be trained and knowledgeable in the operations of the National Weather Service and understand the significance and degree of reliability of the various forecasts issued by the local forecast office. They should be able to translate the various issuances of the National Weather Service into statements about the potential impact of severe weather events on their operations.

3

GEOMORPHOLOGY AND HYDROLOGY DRAINAGES IN THE TUCSON BASIN

Tucson is located in a topographic basin bounded by the Santa Catalina and Tortolita Mountains to the north, the Rincon Mountains to the east, the Santa Rita Mountains to the south, and the Tucson Mountains to the west (Figure 9). The principal watercourses in this basin collect drainage from and flow between these ranges. Like many desert mountain masses, those near Tucson have broad piedmont surfaces extending at fairly uniform slopes of 10 to 30 m/km away from much steeper mountain fronts. These piedmont surfaces may be erosional bedrock surfaces, called pediments, or they may be mantled by fan gravels and dissected by deep washes. The ephemeral streams of the piedmont areas convey water and sediment from the mountain fronts to the valley floors in the basin during occasional rainstorms. Coarser gravel and boulders are deposited mainly on the piedmont, while the finer fraction of the load, including sand, silt, and clay, are conveyed to the valley floors.

The Santa Cruz River begins in the San Raphael Valley along the border with Mexico. The river flows south into Sonora and turns abruptly west and north to reenter the United States east of Nogales. The channel extends northward through Tubac and Green Valley to reach the downtown portion of Tucson. Through much of Tucson the Santa Cruz is deeply entrenched into the sediments of the valley floor. The Santa Cruz drains about 5,800 km^2 to the south of Tucson, including large piedmont surfaces extending from mountains on the east and west sides of its valley. Sediments transported to Tucson are mostly fine sand and silt.

Northwest of downtown Tucson the Santa Cruz River is joined by the Rillito system, which drains about 2,400 km^2 to the north and east of Tucson. The Rillito flows about 20 km along the northern boundary of the city at the base of an extensive piedmont extending from the Catalina Mountains. In northeast Tucson the Rillito is split into two major tributaries, Tanque Verde Creek and Pantano Wash (Figure 10). Pantano Wash collects drainage from extensive areas to the southeast and traverses a long section of basin floor. Because of its length, sediment sizes become relatively fine where Pantano Wash reaches Tucson. In contrast, Tanque Verde Creek transports a relatively coarse load from the nearby Santa Catalina and Rincon Mountains. The coarse sand of Tanque Verde Creek mixes with the finer Pantano sediments to give the

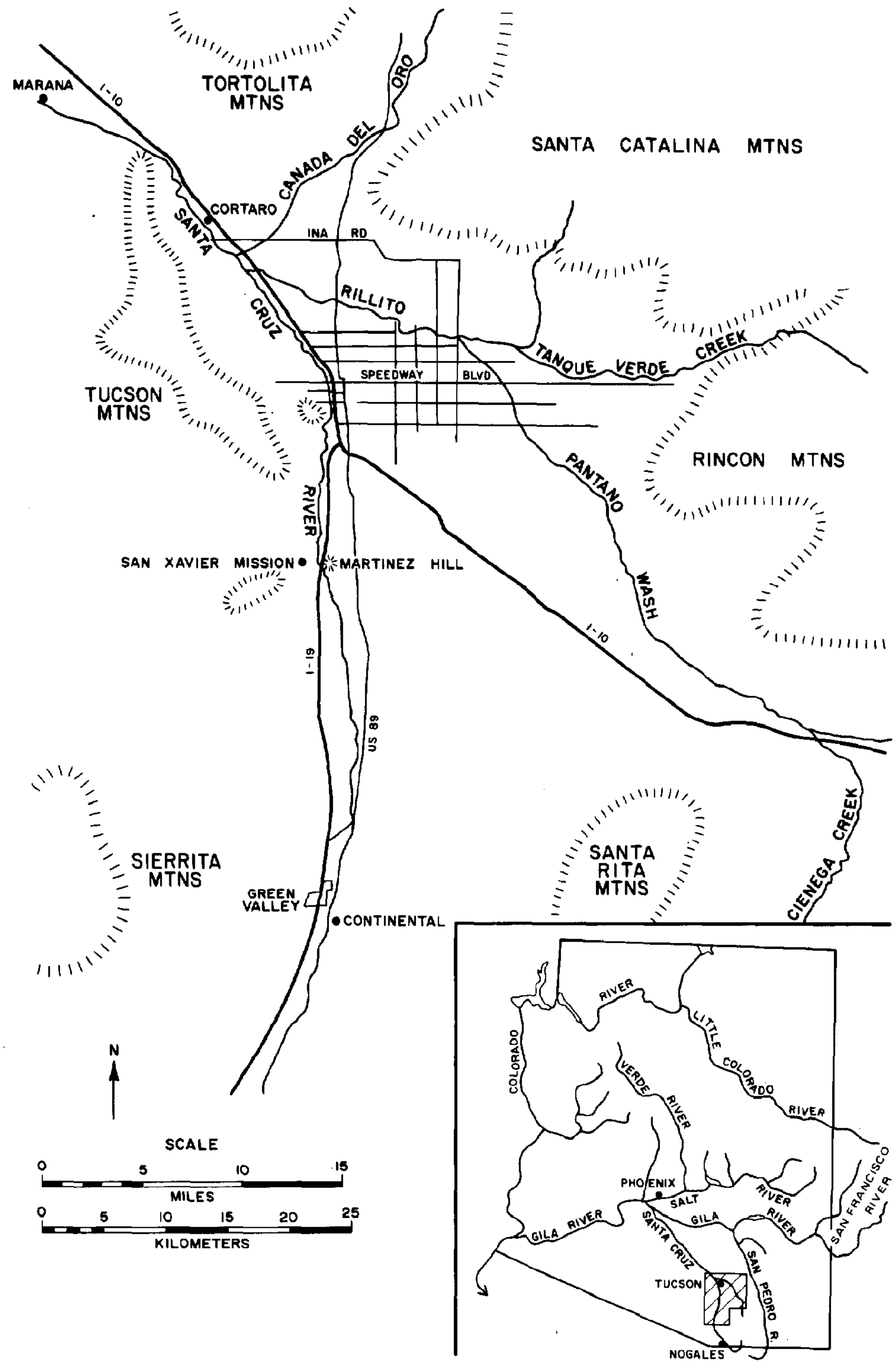

FIGURE 9 Index map of the Tucson Basin showing the principal watercourses, mountain ranges, and transportation routes.

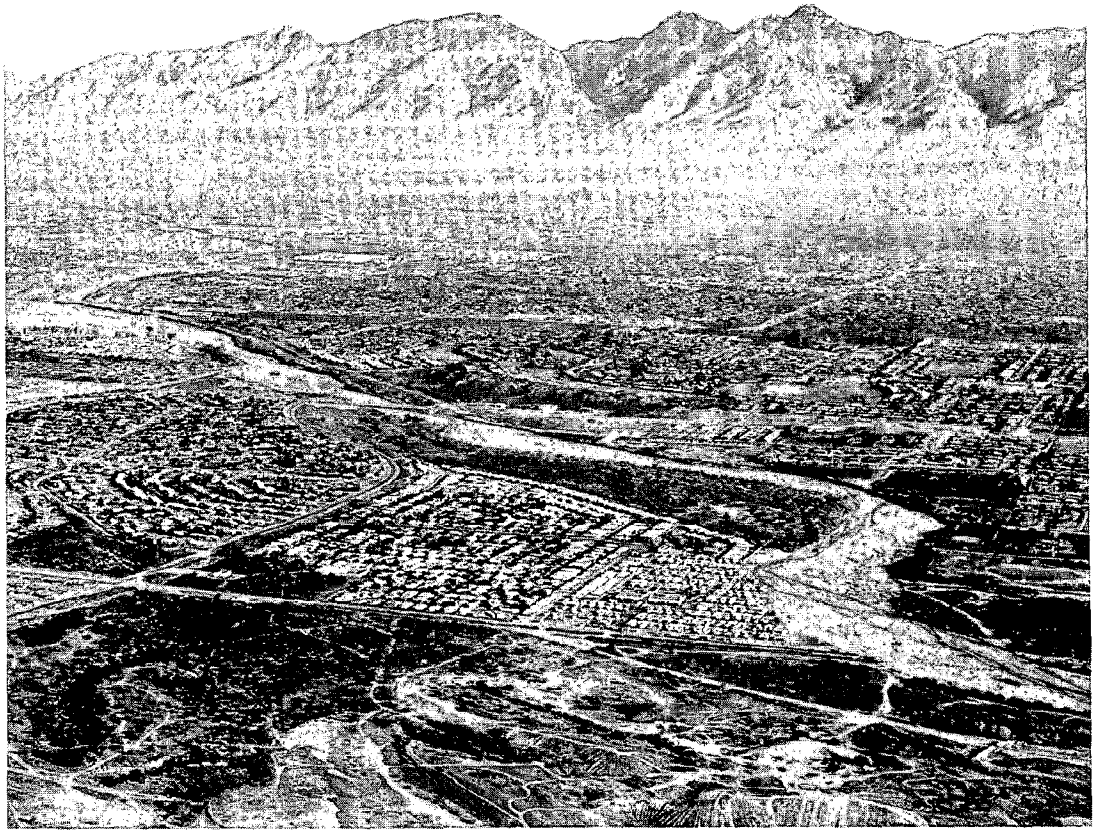

FIGURE 10 Aerial view of the eastern Tucson Basin on October 9, 1983, showing Pantano Wash in the foreground and the Santa Catalina Mountains on the skyline. Flood damage to the Rincon Country mobile home development (bottom center) is shown in Figures 26 and 38. Photograph by Peter Kresan.

Rillito an intermediately coarse sand load, which is then conveyed to the Santa Cruz River, which transports fine sediments. These sediment load characteristics play an important role in the adjustment of the different streams to changing flow conditions.

About 2 km north of the confluence of the Rillito, the Santa Cruz is joined by the Canada del Oro. This stream drains about 660 km^2 from the western slopes of the Santa Catalina Mountains and eastern slope of the Tortolita Mountains.

GEOMORPHIC HISTORY OF TUCSON DRAINAGE COURSES

Floods are usually defined by the damage they do. The flow of water in a stream channel, as studied by hydrologists, is not considered a flood unless it rises sufficiently to cause damage and disruption. In general, flood hazard management emphasizes the economic consequences of rising water levels.

Another view of floods emphasizes their association with the river, the valley, and the valley lands adjacent to the river. This geologic perspective on floods (Moss et al., 1978) is not often incorporated into flood hazard management. In the humid temperate portions of the United States, river channels generally occur within a bottomland surface that is created by the river itself. The river occasionally overtops its banks, carrying and depositing sediment on that surface. This surface is the geologic floodplain of the river. The hazard zones of such rivers show close correlation to this geologic floodplain, since it is inundated relatively frequently. Shallow water might cover it with a 50 percent chance each year, and deep flows with a depth roughly equal to twice the channel bank heights might occur with a 2 percent chance per year (Moss et al., 1978).

The above experience has little applicability to ephemeral sand-bed streams in valley bottomlands of the arid and semiarid West. Streams in that environment may flow directly on broad, low valley floors with little or no channel. In that case every flow event could cause damage, especially as the threads of flow shift on a depositional surface. The contrasting extreme is the incised channel, where the stream has cut through the former bottomlands so deeply that even very rare high flows will not spill out of the incised banks. Both the above conditions may occur on the same stream, either at different localities at a given time or at different times at the same locality. The management of flows in such an environment cannot ignore the geologic complexities of the system. Experience gained in the Tucson flood of 1983 will illustrate this conclusion.

The general channel configurations and cross-sectional shapes on valley floors in the Tucson area today derive from a history of arroyo cutting in the late 1800s and early 1900s. Similar histories are prevalent throughout the southwestern United States, and considerable controversy surrounds attempts to provide a general explanation of the phenomenon (Cooke and Reeves, 1976). At Tucson an extensive historical record allows a precise reconstruction of events associated with the transition of the Santa Cruz from an alluviated valley floor to a narrow, steep-sided channel (Betancourt and Turner, in press).

Prior to the major flood of August 1890, the Santa Cruz River exhibited perennial flow at several reaches near Tucson (Figure 11). The generally high water table intersected the valley floor at these locations and maintained the flow through perennial springs. Two springs upstream of San Xavier Mission, Agua de la Mision and Punta de Agua, served to irrigate fields at the mission. Near such springs small marshes, or cienegas, developed, with lush vegetation, fish, and beaver locally. Reaches between the spring outflows, amounting to 75 percent of the river course in the Tucson Basin, were ephemeral because of infiltration into the dry, sandy riverbed. These reaches were generally marked by shallow swales. However, local sections did have short discontinuous gullies with vertical banks up to 3 m high and 20 m apart.

During the 1880s this system began to reflect a profound human impact. Various impoundment and diversion structures were introduced to

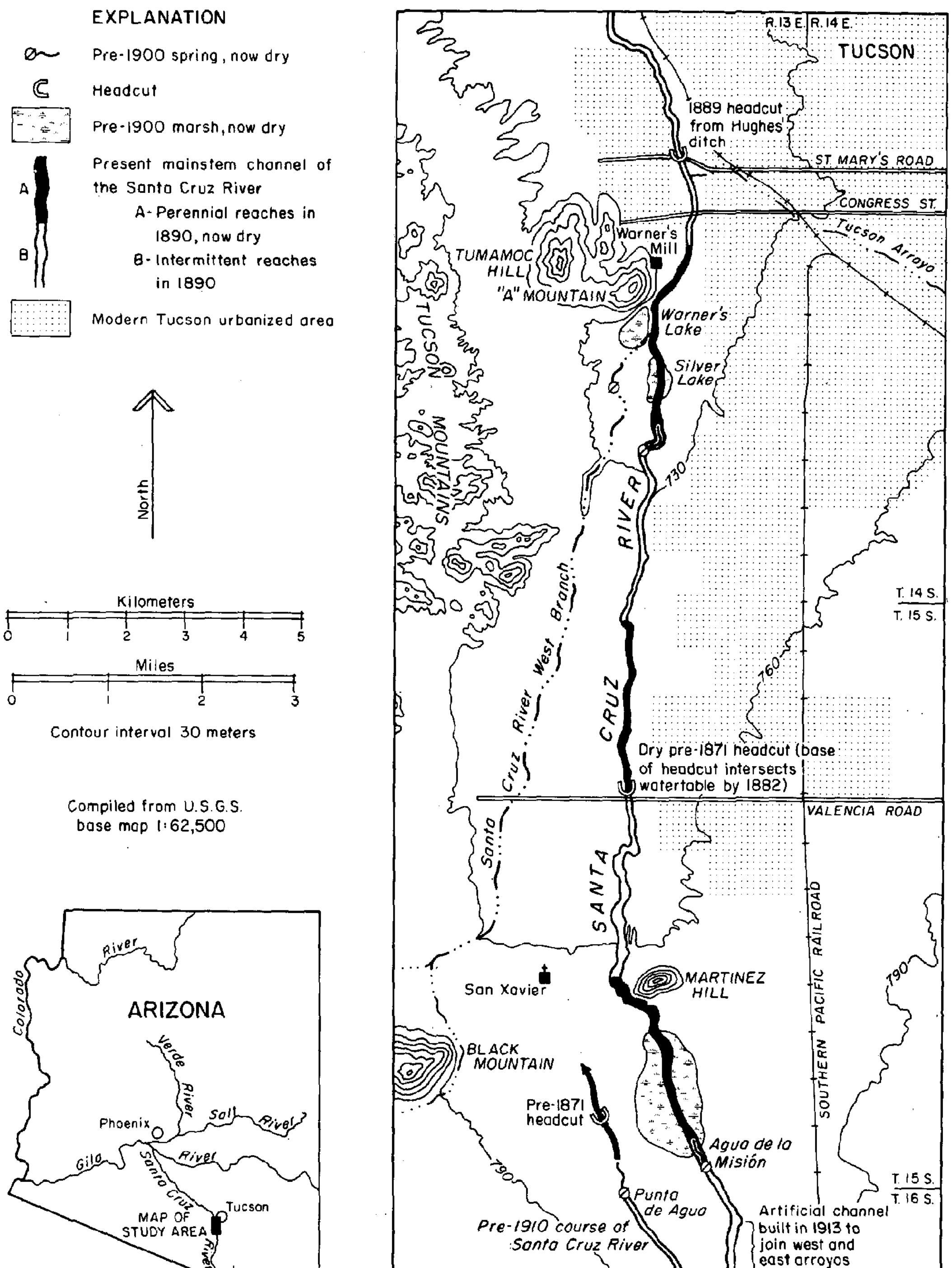

FIGURE 11 Map of a portion of the Santa Cruz valley near Tucson showing the present mainstem channel, perennial and intermittent reaches in 1890, and the location of headcuts and marshes (cienegas) in the late nineteenth century. Source: Betancourt and Turner, in press.

facilitate irrigation on the alluvial valley floor. In 1888 a major ditch was constructed by Sam Hughes near the present St. Mary's Road to intercept underflow in the Santa Cruz alluvium. In October 1889 a relatively small flood cascaded into Hughes' ditch, forming a headcut, or nickpoint. A major flood in July-August 1890 caused this headcut to work its way upstream approximately 4 km to a small impoundment at a former cienega called Silver Lake (Figure 11). The valley floor of the Santa Cruz was now incised with an arroyo about 30 m wide. The headcut continued to recede with each flow event until by 1910 it had reached Martinez Hill.

In the winter of 1914-15 the Santa Cruz experienced several prolonged floods that significantly widened the channel through bank erosion. The Arizona Daily Star on February 1, 1915, recorded the erosion of the east abutment to the Congress Street bridge by bank erosion through meander migration (Figure 12):

> Sudden destructive tendencies developed in the flood that swept down the Santa Cruz River yesterday morning and from 10 o'clock until noon the river rapidly washed away a large section of valuable land enclosed within a wide curve on the east side of the stream just south of the Congress Street road and containing five or more acres, finally about noon destroying more than a hundred and fifty feet [45 m] of embankment that connected Congress Street with the east approach to the bridge. . . . The work of destruction was continued steadily, but more slowly throughout the afternoon and by midnight the rushing water was creeping at the outside of the curve close to the row of cottages just east of the big concrete irrigation ditch and threatening to include the houses in the ruin.
>
> While the river did not rise any higher, it developed a terrific boring power that rapidly crumbled the soft dirt into the swirling current of the muddy Santa Cruz. The current worked with telling effect on the sandy subsoil of the rich arable land of the bottom and the total damage is estimated to be not less than $50,000 at midnight. The east approach to the bridge was swept away leaving 200 feet [60 m] of water between the road and the bridge. The piers of the bridge itself also sank. . . . The sudden driving force that the stream acquired in the morning rendered useless the protective measures taken and there was little that could be done through the day to protect the embankment. Foot after foot went out and by midnight it was estimated that the gap between the bridge and the east end of the road was more than 200 feet [60 m].

With minor changes this description could apply to damage at bridges in the flood of October 1983.

After the floods of 1914-15 the Santa Cruz continued to incise upstream of Martinez Hill (Figure 11). By the 1930s a headcut had migrated from Agua de la Mision up an artificial channel built in 1913 to join the west and east branches of the stream. During the 1920s and the 1930s the incised river near Congress Street began to aggrade. The

FIGURE 12 Erosion damage to the east abutment of the Congress Street bridge on February 1, 1915. The view is upstream (south), and Sentinel Peak ("A" Mountain) is visible at right. The gap of 60 m from the bridge to the east bank (left in picture) resulted from the downstream migration of a meander bend on that bank. This meander bend was visible in a 1902 photograph (Betancourt and Turner, in press). Source: Arizona Historical Society, Tucson.

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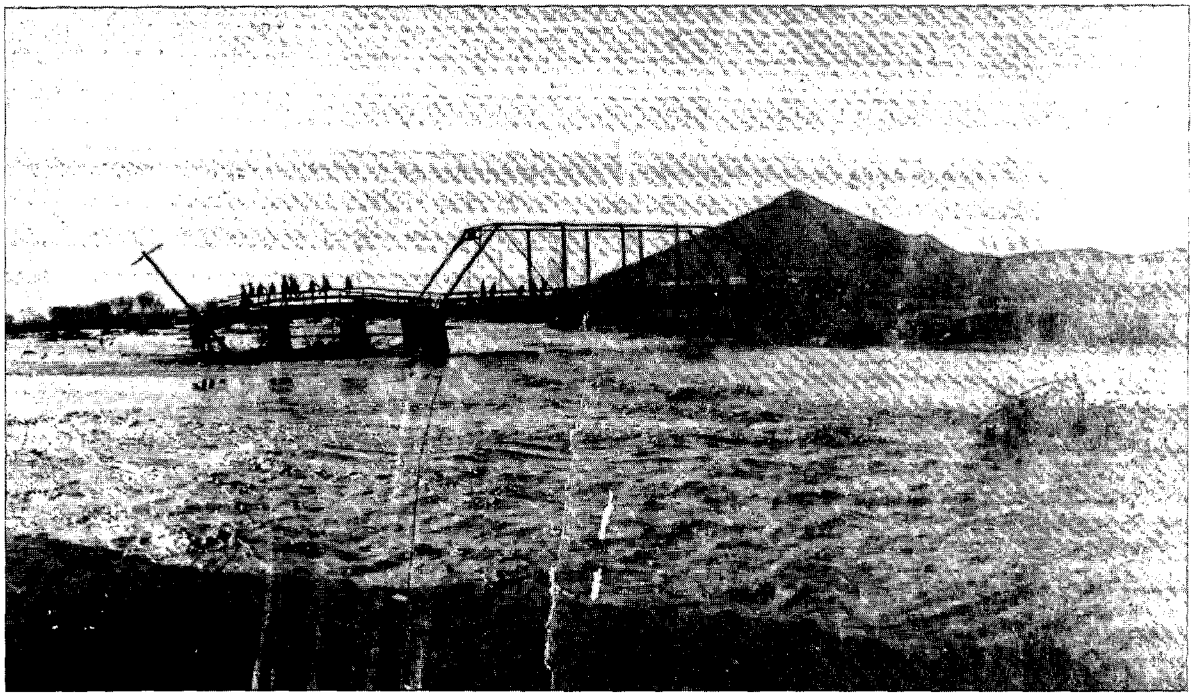
aggradation probably resulted from the decreased velocities achieved by the channel widening in 1914-15, from the stabilizing effect of cottonwoods and other riparian vegetation, and from the lack of major winter floods in this period. Because of their relatively low sediment loads (in contrast to summer floods), winter floods are particularly erosive for the sand-bed streams of southern Arizona.

Starting in 1950 the Santa Cruz through Tucson was modified by artificial narrowing through landfill operations and by highway construction. The reach from Martinez Hill to Congress Street had been straightened in 1935 by the efforts of the Works Progress Administration. Flows were deflected from severe bends by means of revetments. The result of these changes was renewed downcutting by higher-velocity flows through the straightened and constricted channel. The zone of aggradation moved downstream, past all the urbanized reaches, to the far northern end of the Tucson Basin.

The Rillito system had an early history similar to that of the Santa Cruz. From a condition in 1858 that included beaver dams along a broad



valley floor, the stream had incised to a wide channel with vertical banks by 1890. The change was attributed by Smith (1910) to cutting of vegetation, overgrazing by cattle, and flood erosion. Channel incision continued into the twentieth century as excessive withdrawal of ground water eliminated riparian vegetation along stream banks and bars.

Studies of aerial photographs since 1941 show that the Rillito-Pantano-Tanque Verde system has been characterized by prolonged periods of channel narrowing locally interrupted by abrupt periods of widening with attendant bank erosion (Figure 13; Pearthree, 1982). Narrowing from 1941 until 1965 occurred during an interval dominated by short-duration floods with peaks less than 300 m^3/s. Most of these flows occurred in the summer and early fall, and they probably transported very high sediment loads. In 1965 a large winter storm produced a prolonged flood that peaked at about 350 m^3/s for Tanque Verde Creek and the Rillito. This flood carried a relatively low sediment load and generated extensive bank erosion for both stream channels. In contrast, Pantano Wash did not experience this flood and continued to narrow.

After the 1965 event both Tanque Verde Creek and the Rillito displayed either natural recovery or local artificial stabilization. In December 1978 another major winter storm affected these streams. As in 1965, this event, which peaked at 464 m^3/s in the Rillito, was characterized by prolonged duration and a relatively low sediment load. In addition, a flow in March 1978 had removed much of the sediment that had accumulated in the stream channels during the preceding recovery period. Extensive bank erosion occurred during a three-day period of flow. Channel realignment, bank protection, and bridge repair after the 1978 flood led to the general condition of the Rillito-Tanque Verde-Pantano system immediately prior to the 1983 flood.

FIGURE 13 View upstream (east) from the Campbell Avenue bridge on October 1, 1983, showing erosion of the north (left) bank by meander flow. Note the dark thread of high-velocity water following the meander thalweg from the next bend upstream. Also note the utility lines in the stream channel. Photograph by Peter Kresan.

It is clear that the streams of the Tucson Basin have been irreversibly altered from conditions that prevailed prior to large-scale human intervention. A return to the channel characteristics of the 1800s is impossible for the following reasons: (1) groundwater overdraft has so lowered the water table that the stabilizing influence of riparian vegetation has been lost, (2) the urbanization process has reduced the influx of sediments from tributaries into the main channels while increasing the influx of water from individual storms, and (3) channels have been constricted by bridges, filling on banks, and revetment works.

HYDROLOGIC ASPECTS OF THE 1983 FLOOD

The flood peak on the Santa Cruz River at Cortaro occurred between 8:00 p.m. on Saturday, October 1, and 9:00 a.m. on Sunday, October 2 (H. W. Hjalmarson, U.S. Geological Survey, personal communication, 1983). Peak flood discharges have been provisionally estimated for several localities in the Tucson Basin (Table 4). Extensive bank erosion resulted in the losses of gages on major watercourses, but postflood hydraulic calculations are being used to determine flood peaks. Final estimates, hydrographs from undamaged gages, and detailed interpretation are still being generated by the U.S. Geological Survey. However, several conclusions concerning flood frequency seem warranted at this preliminary point.

The Santa Cruz River peaked at 1,490 m^3/s (52,700 cfs) at Congress Street. This event exceeds by more than a factor of two any other flood recorded at that station. It exceeds by a factor of 1.75 the magnitude of the 100-year flood designated in the Federal Emergency Management Agency (FEMA) Flood Insurance Study (Federal Emergency Management Agency, 1982). Even more important is the fact that the FEMA flood magnitudes were adjusted upward from the standard procedures. The problem of estimating a true recurrence interval for this event will be treated below. The Rillito also had an extreme flood (Figure 13), estimated at 840 m^3/s (29,700 cfs). The FEMA-determined return period for this event would be between 50 and 100 years.

In contrast to the Santa Cruz and Rillito, other streams in the Tucson area had floods that were much less extreme in relation to past experience. The Canada del Oro at Overton Road had a peak flow of 185 m^3/s (6,600 cfs), as estimated by the U.S. Geological Survey. This compares with the 10-year flood estimate of 280 m^3/s (10,000 cfs), which the federal Flood Insurance Study for the Pima County Department of Transportation and Flood Control District used as the regulatory flood. Pantano Wash peaked at 310 m^3/s (11,000 cfs), which is between the 10-year discharge of 250 m^3/s (9,000 cfs) and the 25-year discharge of 400 m^3/s (14,000 cfs). The record flow of Pantano Wash at Broadway was 570 m^3/s (20,000 cfs) in 1958.

The annual flood peaks of the Santa Cruz River have been recorded at the Congress Street bridge since 1915. In the period 1915 to 1981 (Figure 14), 73 percent of all annual peaks occurred during July and August, 18 percent occurred during September and October, and 9 percent occurred during November through February. No annual peak flows have been recorded in March, April, May, or June. A standard log-Pearson III analysis of this record is shown in Figure 15. This plot was derived according to standard procedures followed throughout the United States (U.S. Water Resources Council, 1981). This plot estimates the 100-year flood as about 650 m^3/s (23,000 cfs), only half the magnitude of the 1983 flood. By this analysis the return period of the 1983 flood would be more than 1,000 years. This is beyond the frequency of events that are considered in usual hazard management.

TABLE 4 Estimated Flood Peak Discharges and Recurrence Intervals for the 1983 Tucson Flood

Locality	Provisionally Estimated Discharge[a]		100-year Flood Discharge[b]	
	cfs	m^3/s	cfs	m^3/s
Santa Cruz at Congress Street	52,700	1,490	30,000	850
Santa Cruz at Cortaro	65,000	1,840	40,000	1,130
Rillito at Flowing Wells	29,700	840	32,000	900
Canada del Oro at Overton Road	6,600	185	28,000	800
Pantano Wash at Broadway	11,000	310	25,000	700

[a]H. W. Hjalmarson, U.S. Geological Survey, personal communication, 1984.

[b]Federal Emergency Management Agency Flood Insurance Study.

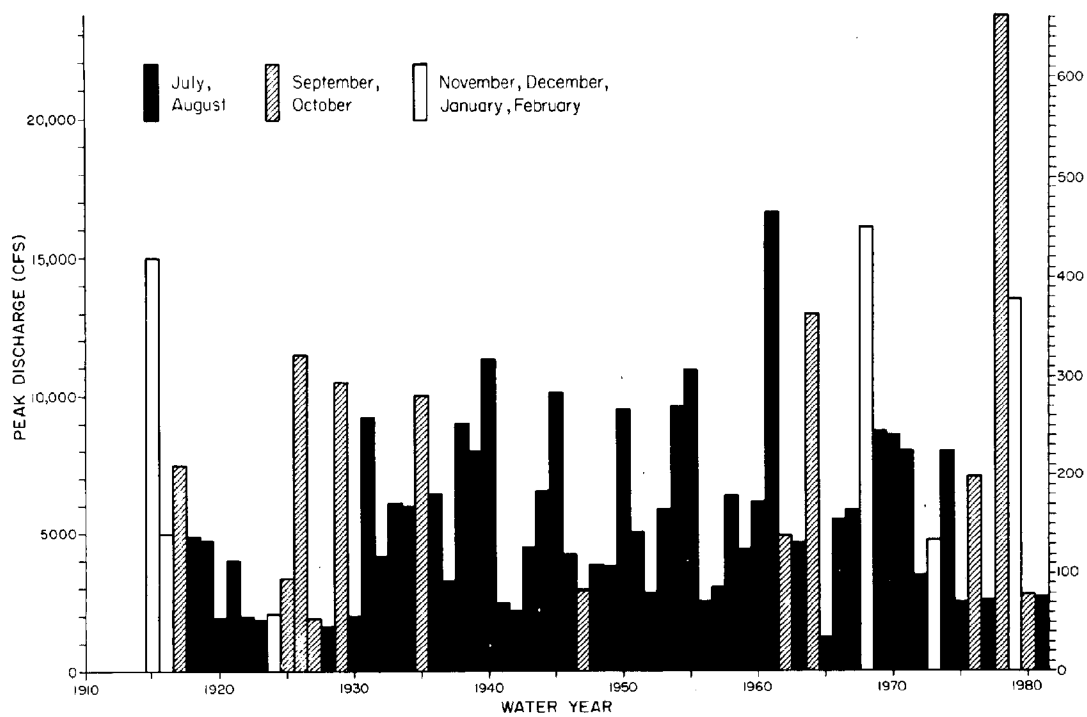


FIGURE 14 Annual peak discharge for the Santa Cruz River at Congress Street between the water years 1915 and 1981. The gage was removed late in 1981. Note the months of peak discharge. Newspaper accounts for the period between 1902 and 1914 also include several major storms in winter. Source: Betancourt and Turner, in press.

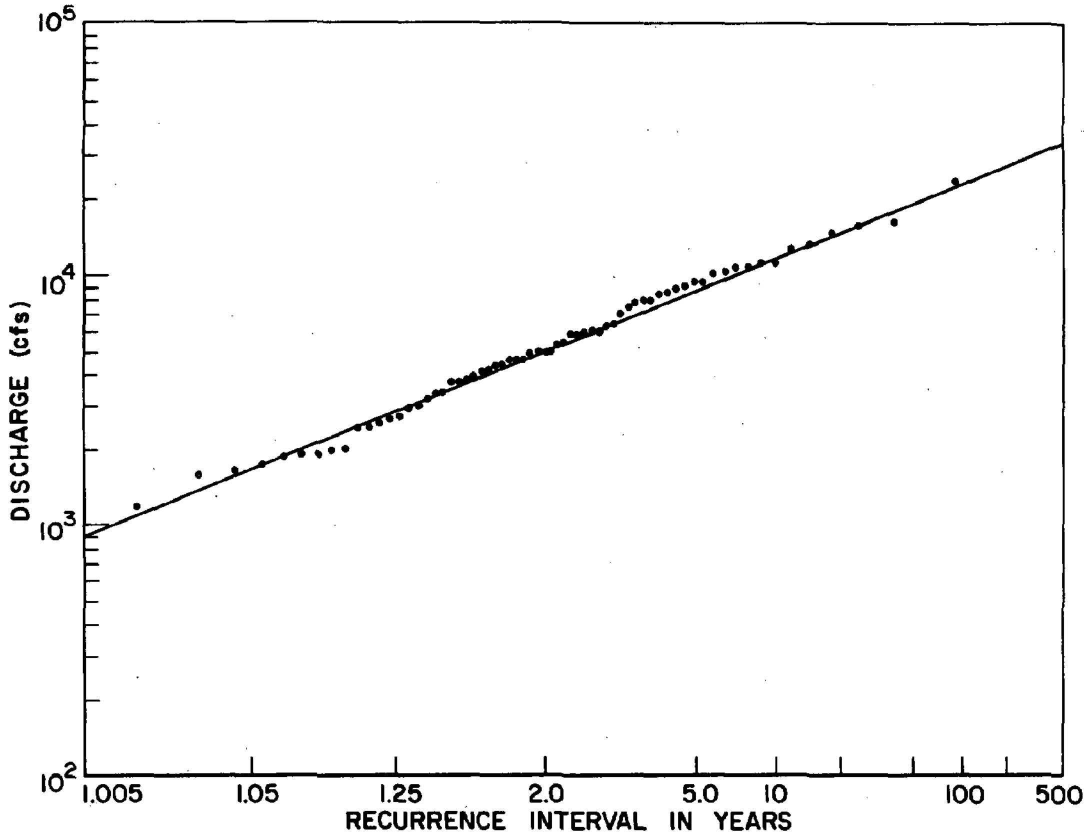


FIGURE 15 Flood-frequency analysis of the 1915-81 annual flood peaks of the Santa Cruz River at Congress Street. The plot was derived according to the nationally mandated procedure (U.S. Water Resources Council, 1981).

Most standard techniques for estimating the recurrence probabilities of flood events assume a stationary mean (U.S. Water Resources Council, 1981). This means that the methods presume a flood history has been extracted from a river whose hydrologic characteristics have not changed over the period of measurement. Clearly this assumption does not apply to the Santa Cruz flood record (Figure 14). From 1915 to 1960 no flood occurred that exceeded 340 m^3/s (12,000 cfs), but since 1960 there have been six such events (including the 1983 flood). Moreover, this change in flood behavior has occurred on a river whose channel has experienced profound morphological change since about 1890. Even more important are probable climatic factors. Note that the big floods since 1960 are predominantly fall and winter events (September through February), as they were in the period 1915 to 1929. However, the smaller annual peaks of 1916 to 1960 are nearly all summer events (July and August). The nature of the storm systems responsible for the flood peaks are clearly different during the latter period of record.

Accelerated channel change and climatic shifts are probable factors in many watersheds throughout the arid and semiarid western United

States. This invalidates the assumption of a stationary mean that is almost universally applied to flood-frequency analyses in these watersheds. It follows that this also invalidates land-use zoning based on nationally mandated flood-frequency analytical procedures that are indiscriminately applied to the arid and semiarid West.

As shown in the next section, the most important geomorphic aspect of the streams in the Tucson Basin is their tendency to alter their cross-sectional shape in response to changes in water and sediment influxes. The streams experience such rapid and large responses to changing conditions that erroneous hazard zonation can arise from conventional engineering hydraulic-hydrologic calculation procedures. For example, these procedures predict the water surface elevation of the 100-year flood in a particular stream channel by assuming that the geometry or position of the channel does not change significantly prior to, during, or after the flood. This assumption is almost always incorrect for the ephemeral stream channels in alluvial basins of semiarid regions. Indeed, the bank erosion of such streams generally presents a hazard to property that exceeds the hazard of damage from floodwater alone.

AN OVERVIEW OF FLOOD EROSION AND DEPOSITION

To assess the regional effects of the Tucson flood, a team of University of Arizona geosciences students surveyed the postflood changes in watercourses throughout the Tucson Basin (Figure 16). The detailed maps of their results are presented in Appendix B. This section briefly summarizes those observations. Because incomplete bank protection was found to be a major factor in localizing bank erosion, a separate section is devoted to that issue.

At Martinez Hill the incised meander train of the Santa Cruz River encounters a bedrock obstruction (Figure 17). Flow is deflected by the obstruction, inducing pronounced bank erosion. Despite extensive riprap revetments, two bridges were lost at this site (Figure 17). The westward meander migration along San Xavier Road was a direct result of the natural deflection of flow by Martinez Hill.

Approximately 2 km downstream of Martinez Hill, at the junction with Santa Clara (Hughes') Wash, the Santa Cruz was modified by a meander cutoff in 1935. This improvement attempted to prevent bank recession by meander migration. The 1983 flood produced extensive erosion in the vicinity of the island created by this cutoff (see Map 1, Appendix B). About 30 m of bank recession occurred on both sides of the artificial cutoff channel. Erosion upstream of the cutoff threatened a city sewer line crossing. After the flood a levee was constructed in the channel to divert flows into the original Santa Cruz meander to lessen the rate of future bank recession near the sewer line.

Downstream of Santa Clara Wash in the vicinity of Valencia Road, the character of the Santa Cruz changes from a broad shallow arroyo, about 200 to 400 m wide, to a deep narrow arroyo about 100 m wide. Bank erosion was less here because mature mesquite vegetation added stability with its deep root systems. The response of the stream through this

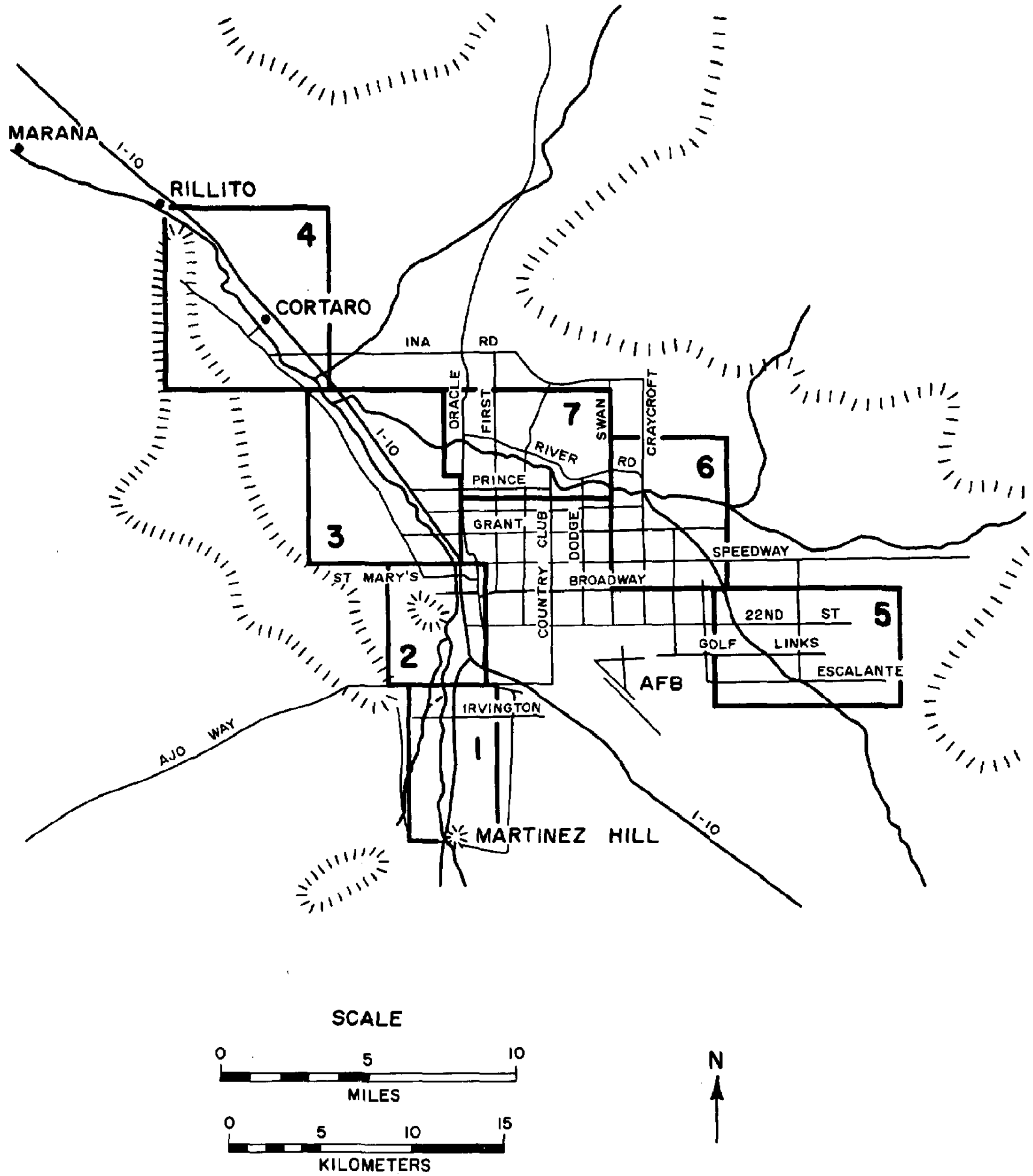


FIGURE 16 Location map of watercourses near Tucson with an index to detailed maps shown in Appendix B of erosion, bank protection, and related flood effects for the October 1983 flood.

reach was mainly by channel scour. Scour of 2 to 3 m can be documented by referring to the preflood footings of high-voltage transmission towers in the channel.

Two prominent meander bends between Valencia Road and Drexel Road illustrate important erosional effects. The cutbank of the upstream

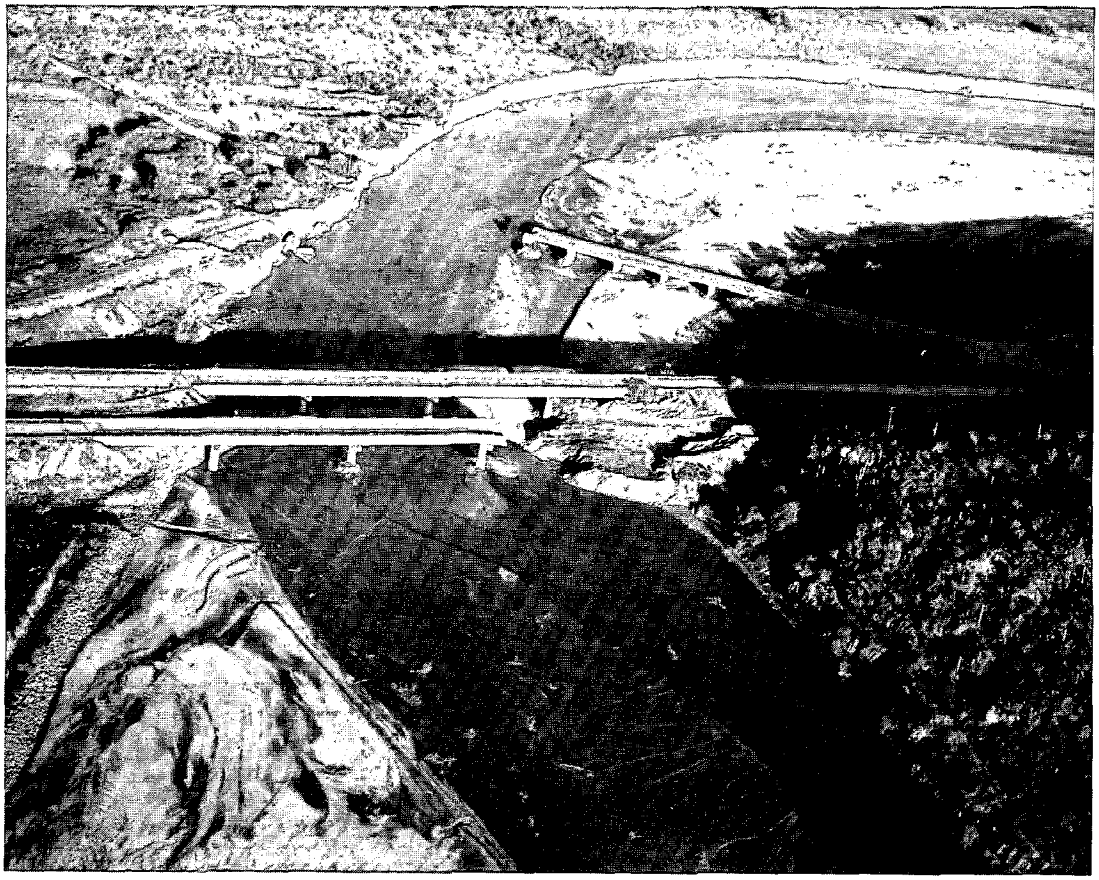


FIGURE 17 The Santa Cruz River at Martinez Hill (lower right) on October 9, 1983. Damage to the north abutment of the northbound lane bridge of Interstate 19 is visible at center. As the flow meandered to the west bank, it eroded the west abutment of the San Xavier Road bridge (top center). Bank erosion extended through the former intersection of San Xavier Road and the access road to Interstate 19 at left center. Note the blocks of collapsed bank material on this bank. Riprap placed along this bank failed to prevent meander migration in the 1983 flood. Photograph by Peter Kresan.

meander bend was protected by 100 m of riprap revetment. Nearly all of this was destroyed during the flood because bed scour undermined the revetment. Approximately 3 m of bank erosion occurred at the bend. Immediately downstream of the protected meander bend, an unprotected bend experienced approximately 40 m of bank recession on its cutbank. The increased erosion at this site is directly related to the protected banks upstream.

Approximately 400 m downstream of Irvington Road, the diversion channel of the West Branch of the Santa Cruz River joins the Santa Cruz main channel. The diversion channel was constructed to lower flood stages at the Midvale Farms subdivision, which lies immediately west of the Santa Cruz River between Drexel and Irvington roads. A concrete drop structure on the West Branch is used to control the gradient change at the confluence, and soil-cement revetments were used to protect channel banks at the confluence. The flood peak in the West Branch is estimated at 85 m^3/s (Brian Reich, City of Tucson, personal communication, 1983). Bank erosion opposite and downstream from these revetments was especially pronounced, averaging about 30 m of recession (Figure 18).

North of Ajo Way an alternating pattern of meander bend erosion continued through an unprotected reach to 29th Street (see Map 2, Appendix B). Between 29th Street and 22nd Street, former meander bends of the Santa Cruz are protected by unsorted debris and/or riprap. Bank erosion occurred at all these bends during the 1983 flood. It was most pronounced where unsorted debris was undermined by scour.

North of 22nd Street to St. Mary's Road the Santa Cruz River is nearly completely confined within artificial banks. The landfill operations near downtown Tucson (Betancourt and Turner, in press) have reduced the stream to a relatively straight channel averaging 50 m in width. This reach is channelized with soil-cement revetment on both banks. Flood discharges through this reach were confined within these artificial banks. Where protected by soil cement, banks were generally unaffected by the flood flows (Figures 19A and 19B). Confinement of flooding to a narrow cross section and reduction of sediment load in the flow because of the protected banks resulted in general bed degradation throughout this reach.

Downstream of Speedway Boulevard the Santa Cruz River channel widens and becomes more sinuous. The 1983 flood caused considerable erosion on the cutbanks of meander bends. Near Grant Road an old sanitary landfill was intercepted by bank recession, spilling refuse into the active streambed. The piecemeal bank protection in this reach showed considerable failure, in contrast with the reach of continuous bank protection lining the channel upstream of St. Mary's Road.

At Fort Lowell Road the sinuosity of the Santa Cruz decreases, and bank erosion by the 1983 flood was less severe than immediately upstream (see Map 3, Appendix B). Some of the stability of this reach can be attributed to riparian vegetation in the channel. Growth of the vegetation was facilitated by an influx of sewage effluent from a treatment plant. Shallow overbank flooding and deposition occurred in this reach.

Downstream of Ruthrauff Road the Santa Cruz showed a major change in character. The channel banks were so stabilized by vegetation that they were unable to enlarge to convey the floodflows. Floodwater spilled on to the adjacent floodplain surface. A secondary channel with a headcut developed on this surface. The width of inundation near Sunset Road was approximately 400 m (Figure 20).

Even greater spreading of the floodflows occurred downstream of the Rillito confluence (see Map 4, Appendix B). Large sand and gravel pits and the Pima County sewage treatment facility are immediately adjacent to the channel. Most of these facilities are along the east banks, with various types of revetments serving to protect that bank. Erosion from the 1983 flood was concentrated on the unprotected west banks.

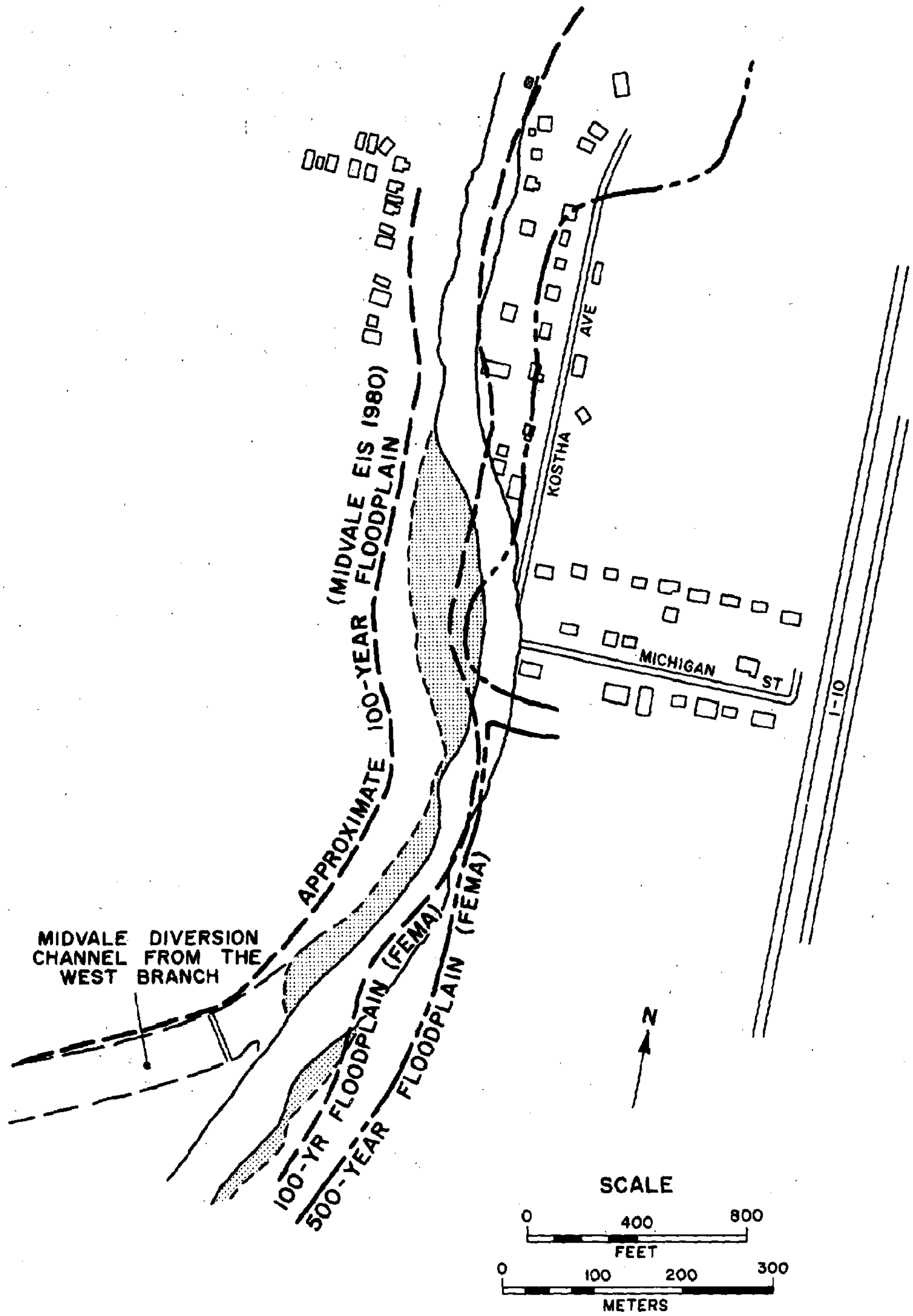


FIGURE 18 Map showing channel migration of the Santa Cruz River from within the 100-year floodplain designated by FEMA in 1982 eastward into areas not designated as hazardous from flooding. Several houses were destroyed near the junction of Kostha Avenue and Michigan Street. The stippled areas are point bars that developed in the October 1983 flood.

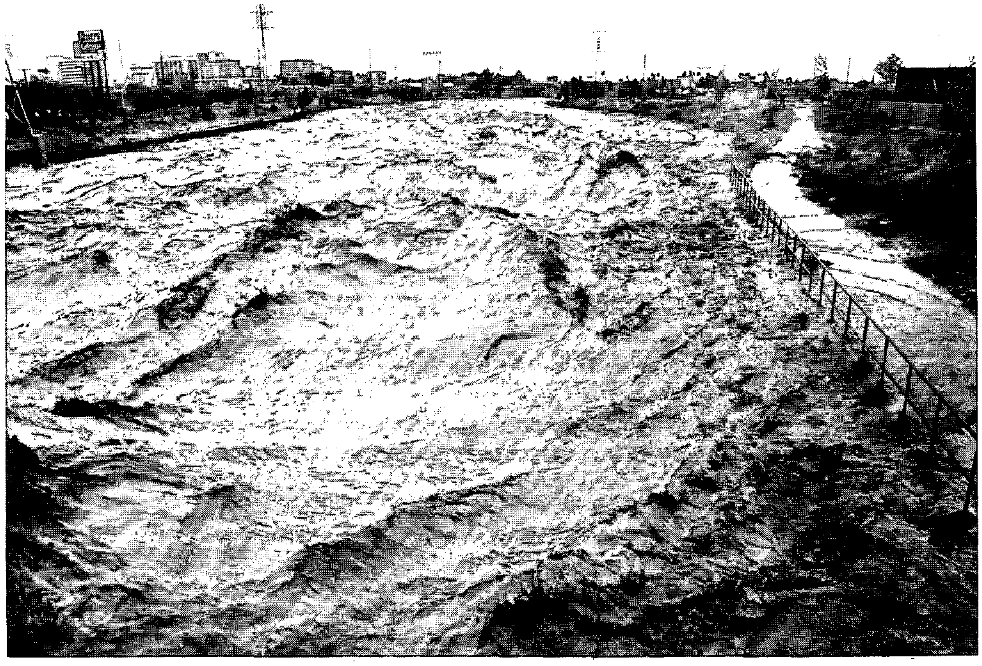


FIGURE 19A View of Santa Cruz River upstream (south) from St. Mary's Road bridge on October 2, 1983. Note confinement of flow within artificial banks composed of soil cement. Photograph by Peter Kresan.

FIGURE 19B View from approximately the same position in late October 1983. Note incision at base of soil-cement slope and meandering thalweg of low-flow channel that developed during waning flow. Photograph by Peter Kresan.

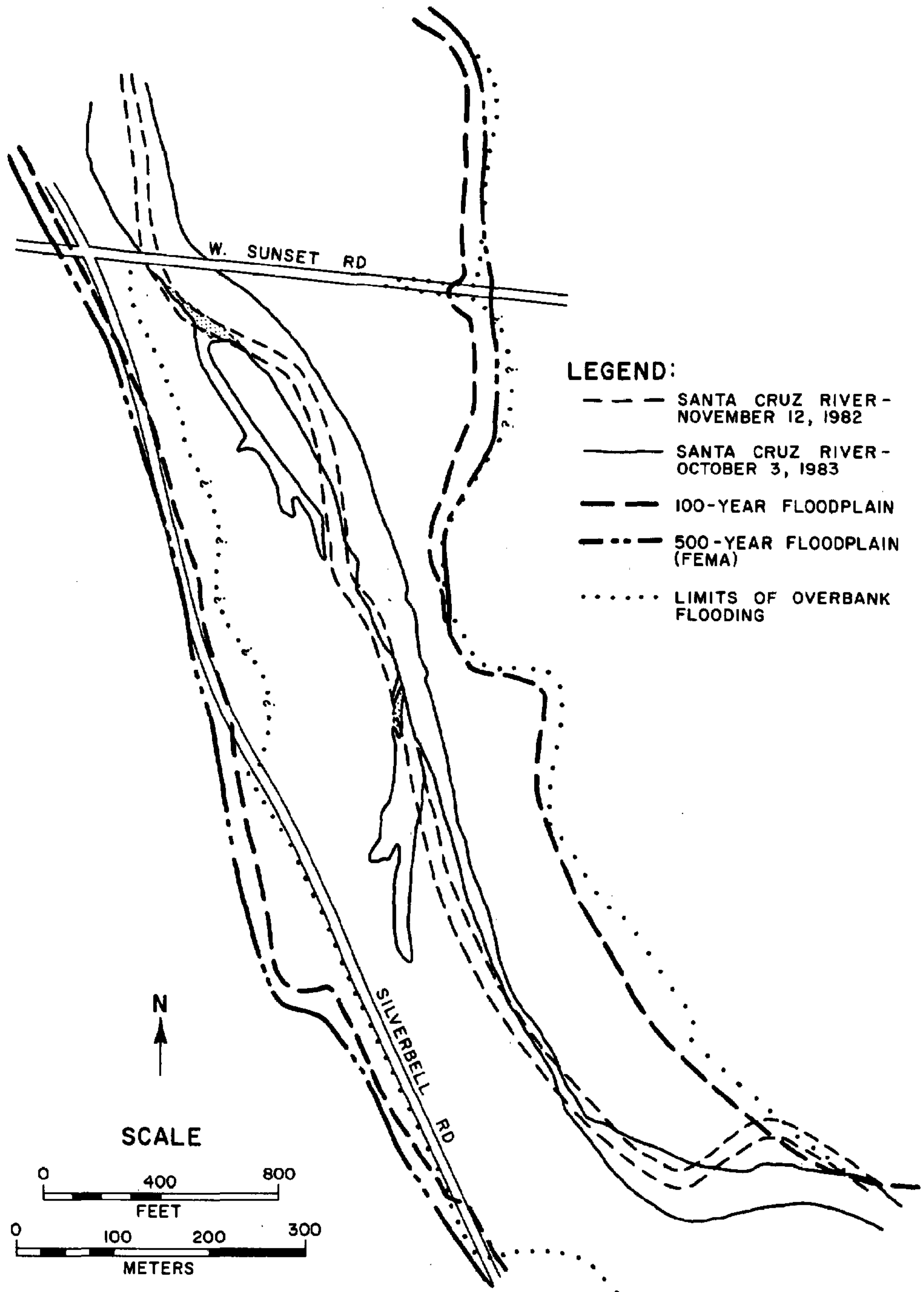


FIGURE 20 Map showing channel changes and FEMA floodplain designations along the Santa Cruz River near West Sunset Road.

At Ina Road spectacular erosion on the west abutment resulted in bank recession that exceeded the original channel width spanned by the Ina Road bridge (Figure 21). Extensive overbank flooding and deposition occurred downstream of this point. Much of Cortaro Road between the Santa Cruz and Interstate 10 was buried by overbank deposition.

A relatively sinuous reach downstream of Cortaro Road was lined with riparian vegetation maintained by sewage effluent. The 1983 flood cut a straight channel through this section and deposited thick overbank sediments to either side of the channel (Figure 22). Note that the Santa Cruz gradually changed to this behavior from an incised, eroding channel near Speedway Boulevard in which the 1983 floodflows were confined.

At Marana (Figure 23) the flooding of the Santa Cruz became a broad shallow inundation over extensive valley floors. Damages to farmland in this region are not described in this report. Significantly, the character of flooding downstream of this point was depositional (Figure 24). Sediment transported from the extensive areas of erosion upstream contributed to aggradation in this area. The aggradation, in turn, led to more extensive inundation. The buildup of sediment from past floods may have so increased slopes in this reach that a new headcut was initiated in the Santa Cruz valley near Picacho Peak (Figure 25).

The postflood erosion survey also documented the behavior of the Rillito-Pantano-Tanque Verde system during the 1983 flood. Pantano Wash was quite interesting because a large drop structure at Broadway separates the system into an incised reach downstream, to the north of Broadway, and a less incised reach upstream, to the south of Broadway (see Maps 5 and 6, Appendix B). Bank erosion from the 1983 flood was minimal upstream of the drop structure. Exceptions were at a prominent meander bend (Figure 26) and at a sand pit north of Golf Links Road.

Downstream of the Broadway drop structure, Pantano Wash is deeply incised. It responded to the 1983 flood by the alternating pattern of bank erosion described above for the Santa Cruz River system. Local areas of bank protection from riprap and wire fence revetment were effective in shifting the concentration of this erosion to unprotected banks. At the downstream end of revetment works around the Tanque Verde Road bridge, a major zone of bank recession caused the loss of residential property.

The upper reaches of Tanque Verde Creek, as with upper Pantano Wash, showed much less bank erosion in the 1983 flood than did entrenched reaches of the Rillito and the Santa Cruz River. Banks were sufficiently low that overbank flooding occurred at the Forty-Niners Country Club Estates. Major bank erosion appeared at the confluence of Sabino Canyon Creek and Tanque Verde Creek. This occurred because of (1) the angle of the stream juncture, which directed flows at an unprotected bank, and (2) changes in sediment loading that occurred as the two flows mixed. The second factor probably also explains the increased erosion that occurred immediately downstream of the confluence of Tanque Verde Creek and Pantano Wash.

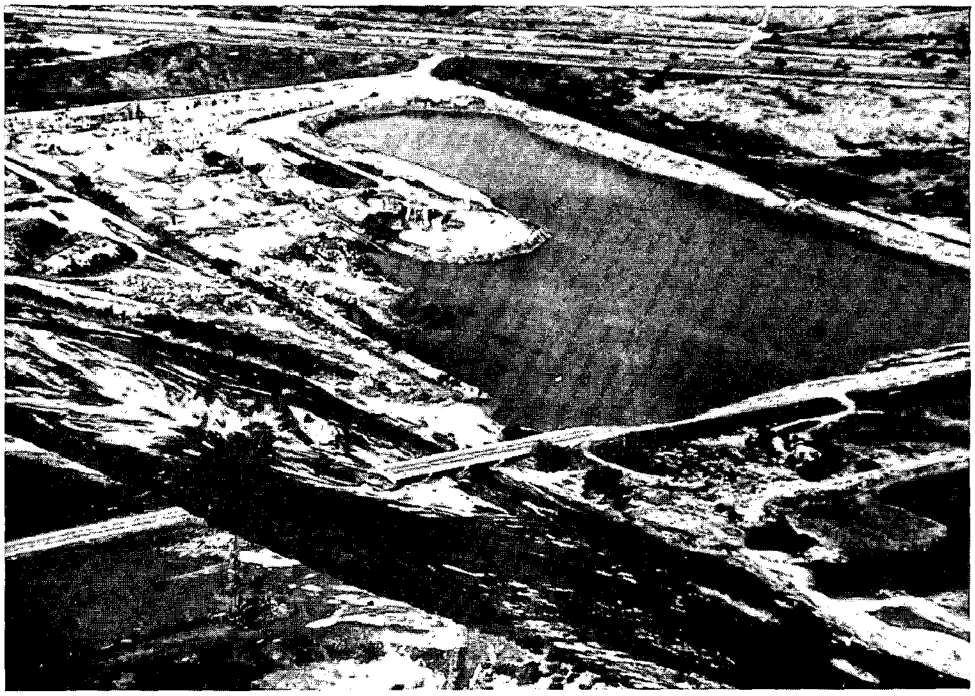


FIGURE 21 The Ina Road bridge over the Santa Cruz River on October 8, 1983, showing extensive erosion of its west abutment. Channel shifting to the west resulted in deposition at the former bridge cross section. Water spilling into the flooded gravel pit (right center) eroded large sections of the eastern approach road. Photograph by V. R. Baker.

The Rillito from Craycroft Road to the Santa Cruz River is an entrenched system. It responded to the 1983 flood by pronounced bank erosion following a pattern of meander bends, as allowed by piecemeal bank protection (see Map 7, Appendix B). From Swan Road to Dodge Road this erosion occurred in a reach that had little bank protection (Figure 27). A major bend at Prince Road resulted in migration of a meander cutbank during the 1983 flood that undermined several houses and townhomes. The bridges at Campbell Avenue and First Avenue (Figure 28) suffered erosion of their northern abutments by meander migration. Many of these effects repeated the experience of floods in 1965 and 1978 (Pearthree, 1983).

AN ASSESSMENT OF BANK PROTECTION

It is clear that unprotected banks in the Tucson area suffered phenomenal erosion during the flood of October 1983 (Figure 29). This hazard has been recognized for many years, and several types of bank protective works were in place at the time of the flood (Table 5). Thus the flood

FIGURE 22 View downstream (north) along the Santa Cruz River north of Pima Farms Road (foreground) on October 8, 1983. The sinuous bends lined with riparian vegetation developed from relatively continuous low discharges from a sewage treatment plant located approximately 5 km upstream of this point. The flood discharge carved a straighter course along the center of the low-flow meander trend. Also note the extensive sedimentation in splay patterns to either side of the central flood channel. Interstate 10 runs diagonally across the top half of the photo, and the Tortolita Mountains are visible on the skyline. Photograph by V. R. Baker.

provided an excellent test of the performance of this protection. The maps of Appendix B document the spatial distribution of this protection in relation to bank erosion.

The experience of the 1983 flood has shown that bank erosion was the most severe hazard encountered on the incised sections of stream channels through the Tucson Basin. To assess the bank protection as a factor in reducing this hazard, two questions can be asked: (1) What was the engineering performance of different bank protection designs--i.e., which designs effectively prevented bank erosion? (2) What was the overall effect of bank protection on the fluvial system? Both questions must be addressed, because piecemeal bank protection can meet the needs of some individuals in protecting their property from bank erosion while the stream system as a whole requires consideration of comprehensive bank protection.

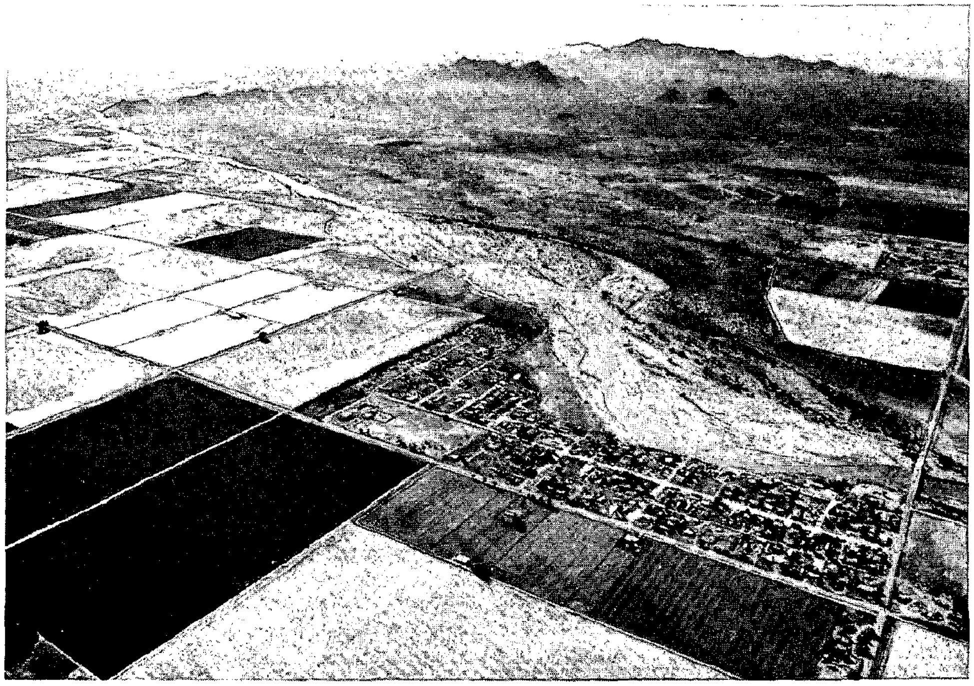


FIGURE 23 View of Marana (center) looking south toward the Tucson Mountains on October 9, 1983. Floodflows in this area spread over extensive agricultural land and caused considerable damage. The prominent meander bend at Marana experienced severe erosion during the prolonged winter flood of 1978. In contrast, the much larger 1983 flood peak resulted in relatively little erosion on this bend. Photograph by Peter Kresan.

Since 1974, the design of bank protective works in Pima County has required the approval of the Floodplain Management Section of the Pima County Department of Transportation and Flood Control District. Nonstandard protective works, including cable-tied automobile bodies and rail, wire, and rock revetment, probably predate 1974 in most cases.

The local effectiveness of the three types of bank protection involving engineering design can be seen by observing the banks of the Santa Cruz River along the 12.8-km reach from Speedway Boulevard to the junction of the Rillito. Riprap revetment was used to protect 2.6 km of bank; wire-fence revetment (with rock fill) was used for 0.5 km. Damage to riprap was more extensive during the 1983 flood. Scour into the streambed is facilitated at the junction between the riprap and the unprotected bed. The rock falls into the scour hole and is either transported downstream or buried in scour holes that develop downstream of individual riprap clasts. Over 80 percent of the study reach protected by riprap showed at least some undercutting and bank recession. In contrast, the wire-fence revetment generally showed damage only on the upstream and downstream ends of protected banks. Scour at those sites caused banks to recede behind the revetments. The soil-cement

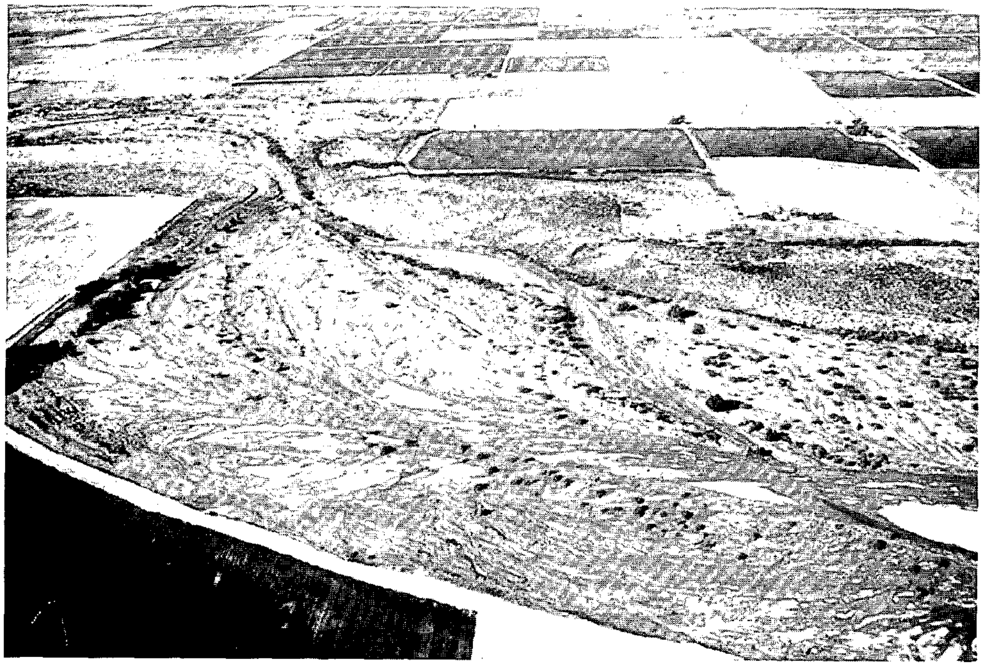


FIGURE 24 Depositional patterns on October 8, 1983, produced by the flooding of the Santa Cruz River immediately downstream of Marana. Photograph by V. R. Baker.

FIGURE 25 Headcut on the Santa Cruz valley floor immediately south of Picacho Peak, 15 km northwest of Marana, on October 8, 1983. Photograph by V. R. Baker.

FIGURE 26 Pantano Wash at the Rincon Country mobile home development (upper right) on October 9, 1983. Escalante Road runs along the top (south) end of the photograph. The prominent bend of Pantano Wash at the top center undermined several mobile homes, which can be seen in the channel at the center and bottom of the photograph. Several automobiles were also incorporated into the northward flow of Pantano Wash. A ground view of the channel at this location is shown in Figure 38. Photograph by Peter Kresan.

FIGURE 27 The Dodge Road bridge over the Rillito on October 9, 1983. Damage to the north (left) abutment was caused by meander migration. Note the prominent cutbank on the north side and corresponding point bar on the south (right) side of the stream. The meander bend immediately downstream (bottom right) is threatening an electric utility station. The anomalously wide section of channel at the top center was the site of a preflood channel sand-mining operation. Photograph by Peter Kresan.

FIGURE 28 The Rillito at the First Avenue bridge on October 9, 1983, showing meander migration on the south (left) bank, which undermined the office building complex in the upper left of the photograph. The return flow to the opposite bank at the upper right damaged the north (right) abutment of the bridge. Temporary repair had been effected at the time of this photograph. Figures 35 and 36 show damage to the office buildings. Photograph by Peter Kresan.

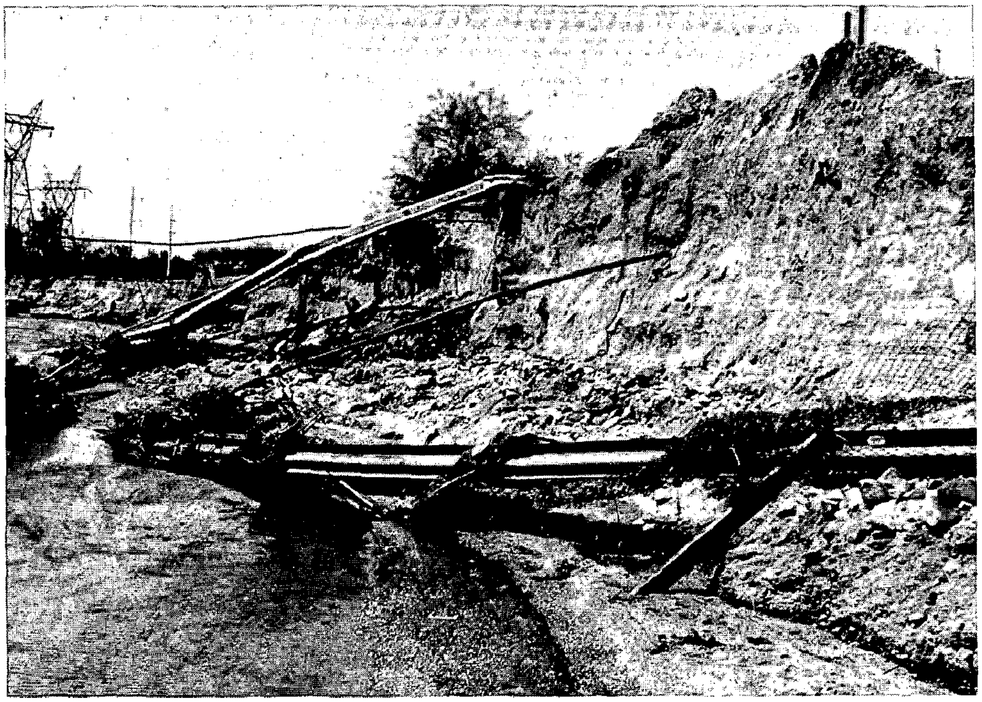


FIGURE 29 Bank erosion along the Rillito at the Dodge Road bridge on October 10, 1983. Photograph by Thomas F. Saarinen.

revetments were undamaged, although prominent erosion of banks occurred immediately downstream of the protection.

The mode of destruction for wire-fence revetments was generally not by scour, as for unconfined riprap. Rather, progressive erosion at the upstream or downstream end of the revetment would scour behind the protected bank. In extreme cases the former bank facing would be isolated in midchannel as the bank receded away from it (Figure 30).

Failure of soil-cement revetment was observed at several localities. Inadequate keying of the soil cement to the upstream or downstream terminus of the protection was the major cause of failure. At Prince Road and the Rillito, a prominent meander bend scoured behind the upstream end of a soil-cement revetment, resulting in major damage to a complex of townhouses (Figure 31).

An example of a properly keyed revetment is the protection for the southeast abutment of the Sabino Canyon Road bridge over Tanque Verde Creek (Figure 32). The pronounced channel widening upstream of the revetment terminates abruptly at this key.

Major bank erosion occurred immediately downstream of reaches that had been extensively protected with soil cement on both banks. An example is the reach of the Santa Cruz immediately downstream (north) of St. Mary's Road. Soil-cement revetments continuously line both banks of the Santa Cruz for nearly 2 km upstream of this point. Erosion appeared

TABLE 5 Types of Stream Bank Protection Observed in Watercourses of the Tucson Basin

Type of Protection	Description
Soil-cement revetment	Embankment facing composed of 8 to 15 percent portland cement mixed with natural bank material. Soil is removed, mixed with cement, and laid on the prepared bank surface in thin layers. The revetment extends to below the level of channel scour and is keyed into the banks at the upstream and downstream termini.
Wire-fence revetment	Wire enclosures held by vertical steel members (often rails) and filled with boulders. A variety of this revetment consists of wire baskets of rock called gabions.
Riprap	A blanket of boulders that exceed the competence of the largest floodflows. The material is used as facing for the bank.
Unsorted debris	Any material dumped directly on stream banks to prevent erosion. Commonly used materials are automobile bodies, concrete blocks, demolitions waste, crushed rock, poured concrete, and rubbish.

immediately at the terminus of this protection (Figures 33A and 33B). It was sufficiently intense to scour the terminus of the soil-cement bank itself (Figure 34). The postflood erosion survey (Appendix B) found that severe erosion occurred at the downstream terminus of every protected bank along deeply incised reaches of the Santa Cruz and the Rillito. Clearly, piecemeal bank protective works concentrate areas of eroded as well as protected banks, and the erosive consequences of such protection should be considered in the overall management of the river system.

The necessity of protecting bridges from loss during floods unavoidably generates a need for localized bank protection. As observed in the 1983 flood, the loss of a bridge most often occurs by bank recession at one abutment. The recession is generally associated with meander migration during the flood. To protect the bridge abutments, a reach both upstream and downstream must be lined with bank protection. The natural tendency of the stream in flood to widen its channel and incorporate added sediment load is thus impeded in the bridge reach. The stream will therefore attempt to scour the streambed at the bridge section,

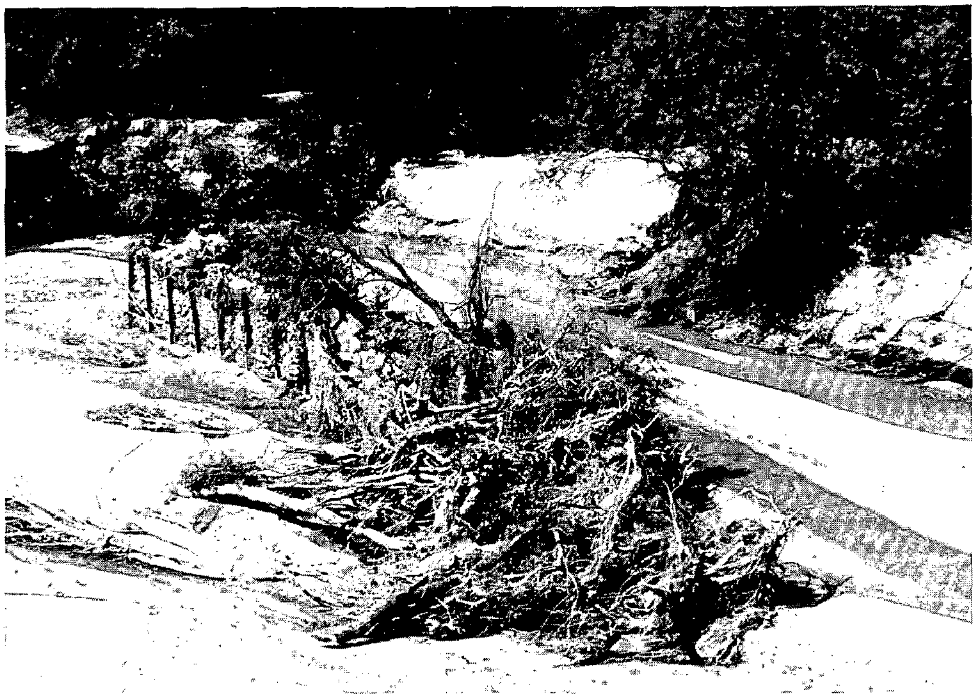


FIGURE 30 *Erosion of bank protected by wire-fence revetment along the Rillito at Craycroft on October 10, 1983.* Photograph by Thomas F. Saarinen.

leading to failure by an undermining of the bridge piers. If degradation control structures are placed on the bed to prevent scour, the bridge reach is transformed into a rigid-walled flume. High-velocity, sediment-impoverished floodwater passing through the protected bridge reach will be erosive in the reach immediately downstream. As in other examples, given several floodflow events, partial bank protection will beget the need for more bank protection.

SAND AND GRAVEL OPERATIONS

In southern Arizona it is a common practice to mine sand and gravel from active channels by excavating shallow pits in their beds (Bull and Scott, 1974). These operations move from place to place as local areas are depleted and flow events modify older workings. The effects of such gravel mining are extensive along the Rillito-Pantano-Tanque Verde system.

The responses of a stream to the lowering of the bed at sand and gravel pits include the following: (1) upstream bed degradation, (2) bank sloughing near the pits, (3) bank erosion caused by temporary water diversion structures used to protect mining operations, and (4) downstream bank erosion caused by the "sediment trap" action of some pits.

FIGURE 31 The Rillito near Prince Road (lower left) on October 8, 1983. Damage to the Pima Park Townhomes (center) occurred when the prominent meander bend at the bottom center migrated west (left) into the vacant property immediately upstream of the townhouses. This allowed erosion to occur behind the soil-cement bank protection lining the stream at the townhome property. The prominent point bar at the bottom center developed as the meander migrated westward. Photograph by V. R. Baker.

FIGURE 32 Soil-cement revetment works lining both banks of the Tanque Verde Creek immediately east of the Sabino Canyon Road bridge (top left) on October 8, 1983. Photograph by V. R. Baker.

The latter problem arises when a pit traps enough sediment entering its upstream end that the outflow from the pit is sediment impoverished and therefore erosive immediately downstream of the pit.

Along the Santa Cruz River, extensive sand and gravel pits have been developed on the surface of the valley floor immediately adjacent to the entrenched channel of the river. At Ina Road a major pit contributed to the undermining of the approach road to the Santa Cruz bridge (Figure 21). A large abandoned sand pit on the Rillito occurs midway between Swan Road and Dodge Road (see Map 7 in Appendix B). The pronounced meander bend erosion downstream of this point, including the erosion of the north abutment of the Dodge Road bridge, may be at least partly related to this sand pit (Figure 27).

The specific changes in the river system described above for the Tucson flood of October 1983 are in keeping with the general long-term characteristics of southwestern streams, as outlined in the next section.

STREAM CHANNEL STABILITY IN THE TUCSON BASIN

Reports of the U.S. Geological Survey in the 1890s note that while runoff in Arizona is very low, at times floods occur whose violence and duration are phenomenal. This is still true. It is also true that no stream flowing north to the Gila River in Arizona or New Mexico has a permanent discharge at its confluence with the main channel.

FIGURE 33A View downstream (north) along the Santa Cruz River from the St. Mary's Road bridge on October 2, 1983. Note that the soil-cement banks confine the flow for approximately 100 m beyond the bridge. Pronounced bank erosion occurs at the distal end of this protection, especially on the west (left) bank, toward which the flow is directed. The high-velocity thread of the flow is marked by antidunes and standing waves. Photograph by Peter Kresan.

West of the San Pedro River, even floodflows rarely reach the Gila River. East of the San Pedro River, streams frequently flow to the main stream. Because the transported sediment has to be deposited as discharge declines, western streams are aggrading, but irregularly so. Water spreads widely among areas of deposition and flows over relatively small intermittent channels. Head cutting may be present at high discharges. Under pristine conditions of a high water table, some local permanent water may occur.

Upstream from areas of deposition, river channels are well defined, but again the characteristics of the channel are determined by the discharges of water and sediment. Under natural conditions upstream from the junction of the Santa Cruz and Rillito, the channels were

FIGURE 33B View from approximately the same position on October 16, 1983. Note that the west bank has receded further from its position on October 2. Damage to the distal end of the soil-cement bank protection on the east (right) bank is shown in more detail in Figure 34. Photograph by Peter Kresan.

alternate reaches of incision and deposition, depending on the relative inflow of water and sediment from tributary streams. On a larger scale this is equivalent to the discontinuous gully system.

The stability of this system, such as it is, depends on a supply of sediment that increases with increasing discharge, on vegetative protection of stream banks, or on valley fill. Because the various tributaries to a stream system do not have equal ratios of transported sediment to water discharge, the stability of a system will vary in different reaches of the stream. Also, because sediment transport increases with increasing intensity of rainfall, the ratio between water and sediment varies seasonally. Because sediment moves as slugs, the ratio of water to sediment decreases with succeeding years of high discharge. Eventually the duration of above-normal discharges probably exerts more influence on stream behavior than do peak flows.

The City of Tucson has been built on this unstable system. The

FIGURE 34 View downstream (north) along the Santa Cruz River between the St. Mary's Road bridge and the Speedway Boulevard bridge (visible at top center) on October 10, 1983. The distal terminus of the soil-cement bank protection has been eroded by the flows shown in Figure 33A. Photograph by Thomas F. Saarinen.

increasing demand for water by this growing city can be met only by tapping groundwater in larger and larger amounts. The result has been a lowering of water tables and the disappearance of streamflow at low rates. Downstream of the city, sewage effluent has increased and currently flows as far as Red Rock. The result has been the almost complete disappearance of riparian vegetation within the city. Except where controlled by structures, the streams have become incised, perhaps by as much as 6 ft, over the last 50 years. Cook and Reeves (1976) and Betancourt and Turner (in press) have documented the effects of man's activities on the Santa Cruz River through Tucson.

The city and its built-up environs now cover over 100 square miles. As a result, storm runoff with a low concentration of sediment has increased. Over the last six years there have been more than average winter floods, each finding smaller amounts of sediment to move. Normally, degradation of the main stream increases the sediment discharge from tributary streams, but the construction of roads and other developments paralleling the river has prevented this.

The result has been increasing bank erosion at different points on the streams. If, over a period of the next few years, winter runoff declines while summer thunderstorms increase, the amount of sediment available for transport in winter storms will increase, improving stream stability. If not, bank erosion associated with channel meandering is to be expected. Over time, however, the incised streams in the Tucson Basin will probably become wider and deeper.

The widespread flooding below the junction of the Santa Cruz and Rillito was caused by the magnitude and duration of the stream discharge during the October 1983 flood. While such flooding could be controlled by levees, it is questionable if this is desirable. Control of flooding would push the locus of spreading downstream and could possibly cause incision of the channels. Levees might also interfere with the use of sewage effluent for irrigation. Most important, levees would reduce the area of groundwater recharge in the area of heaviest pumping.

Whatever is done, it should be realized that an area of deposition will constantly grow and that it is basically unstable from either small or large floods.

Because of the expanding developed area in the Tucson Basin, there is no reason to presume that the present problems of bank stability can be reversed naturally. As long as sediment transport is small in terms of discharge and stream gradient, there will be problems of bank erosion. Many reaches of the stream have been protected, at least on one side, by different types of revetments. Most have worked reasonably well. But, in all locations noted, excessive bank erosion has resulted downstream of the revetted area. Bridges pin the location of the stream and limit the possible variation in bank position and river slope. If the stream is fully revetted, the stream can be expected to degrade its channel in some areas and thus undermine the revetments.

No program for the prompt construction of channel revetments through the built-up area can be expected. Such construction will likely be on a piecemeal basis and simply shift the areas of intense erosion. Without bank protection, erosion will continue until a new equilibrium is reached. The state of the art cannot predict what such an equilibrium will be.

One major grade control structure has been built on Pantano Wash. Theoretically, a reduction in slope should result in a narrower channel. The behavior of this stream should be closely observed, because its sediment transport is reduced when the stream flows into pits excavated for sand and gravel. This should result in a wider channel downstream and might cause degradation below the structure.

Little information is available about the hydraulics of the rivers in the Tucson Basin. There are no sediment sampling programs and few if any actual discharge measurements at high flows, and the county has abandoned its regular measurement of stream discharge. Because any available method of calculating discharge at high flows has a probable error of ± 40 percent, the effectiveness of any design is uncertain.

This situation is not unique to the Tucson Basin. It exists everywhere. John F. Kennedy's 1983 paper, "Reflections on Rivers, Research, and Rouse," should be required reading for anyone working with fluvial hydraulics.

TYPES OF DAMAGE TO PROPERTY

An exhaustive survey of property damage is beyond the scope of this report. Other flood studies have documented damage to property by inundation (Beal, 1983). The focus here is on damage associated with pronounced channel erosion. Damage to various bank protective works was described in an earlier section of the report. Figures 30, 31, and 34 illustrate the types of damage incurred.

Damage to buildings was predominantly from undermining of foundations by bank recession. The office building complex immediately southeast of the First Avenue bridge was undermined by the migration of a meander bend upstream of that bridge (Figure 35). Collapse of the structure progressed as flows continued to erode unprotected banks (Figure 36). The Pima Park Townhomes (Figure 37) were undermined despite protection by a soil-cement revetment. Although the damage can be traced to improper keying of that revetment, the experience shows that even the best type of bank protection will not necessarily provide 100 percent control of the hazard. Mobile homes and vehicles were introduced into the flooded stream channels either by undermining (Figure 38) or by floating in overbank flows. In a major flood, these large pieces of debris can pose a hazard by blocking narrow channel reaches, such as bridge underpasses.

Other sections of this report have summarized the failures of bridges (see Figures 17, 21, 27, and 28). Table 6 summarizes these failures. In most cases, failure was by the erosion of one abutment (Figure 39), generally by the migration of a meander loop at that point. Careful study of the flood erosion and sedimentation survey (Appendix B) reveals a systematic pattern of erosion at meander loops, much of it directed or otherwise facilitated by the extant piecemeal bank protection. Eroded abutments left breaches in the roadways (Figure 40) that closed many highways during and after the floods.

Power lines along both the Santa Cruz River and the Rillito were severely damaged. Power line poles near channel banks were toppled when bank recession undermined their support pads. Other poles and towers had deep footings in bed or bank materials that were exhumed by channel bed scour, causing some towers to topple and others to be severely imperiled by subsequent flows. Along the utility right-of-way for the Santa Cruz River from Valencia Road to the confluence of the Rillito, the postflood erosion survey counted 28 high-voltage electric towers that were severely damaged or destroyed. Another 13 low-voltage poles were twisted or toppled in the reach of the Santa Cruz from Grant Road to the confluence of the Rillito. One hundred meters west of the Dodge Road bridge, a Tucson Electric power station was threatened by 15 to 25 m of bank recession on the Rillito (Figure 27). As shown in Figure 27, bank erosion ceased prior to undermining structures at the power station. The many damaged high-voltage poles in the Rillito utility right-of-way were not counted in the survey.

Damage to sewer line crossings of the major washes is a major concern, since considerable recharge to the principal aquifers occurs through the sandy streambeds. A municipal sewage line was threatened on the Santa Cruz approximately 1.6 km north of Martinez Hill. A levee was

FIGURE 35 Damage to an office building complex caused by the undermining of the bank of the Rillito at First Avenue. An aerial view of this site is provided in Figure 28. Photograph by Tad Nichols.

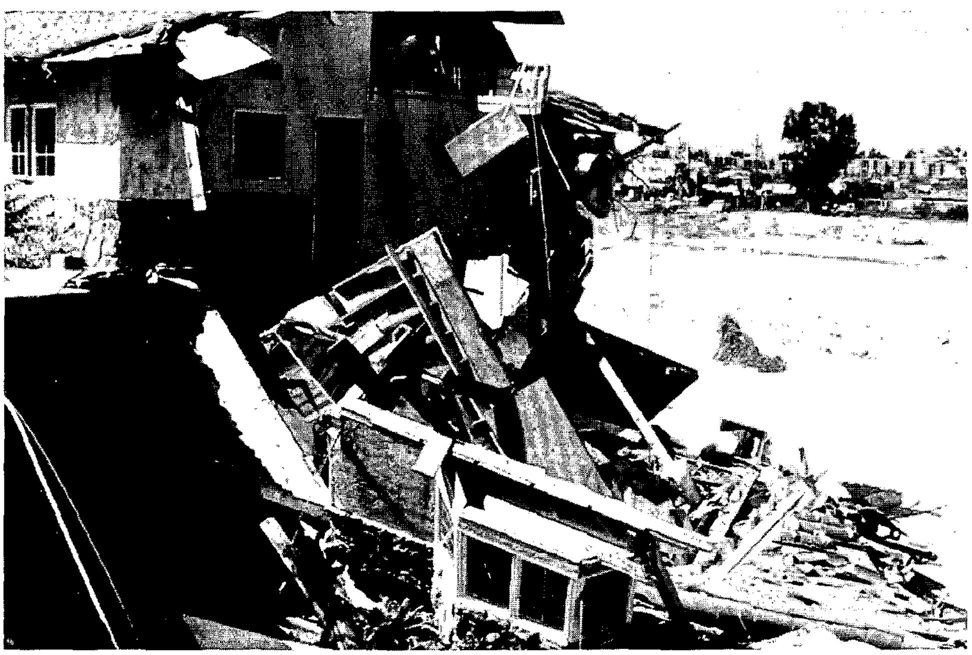


FIGURE 36 Damage to an office building adjacent to unprotected channel banks along the Rillito immediately upstream (east) of the First Avenue bridge. Photograph by Thomas F. Saarinen.

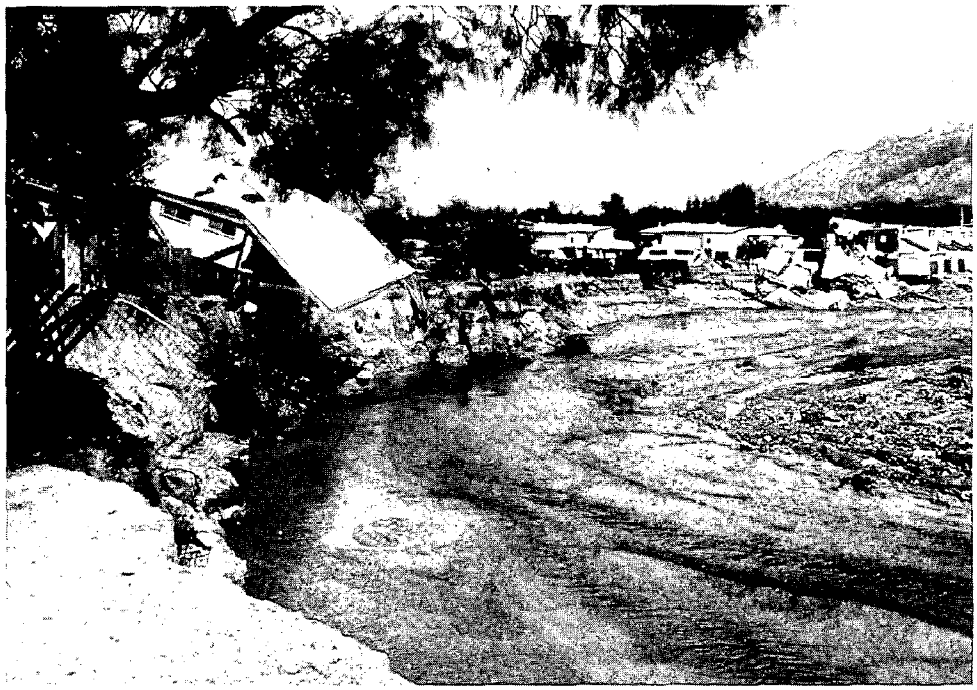


FIGURE 37 View downstream (northwest) along the Rillito from the terminus of Prince Road (lower left) on October 8, 1983. Compare this picture with the aerial view that includes the same reach (Figure 31). The house in the left foreground has toppled into the active meander cut slope. Damage to the Pima Park Townhomes is visible in the right background. Photograph by Thomas F. Saarinen.

constructed in the channel after the flood from channel sediments to divert relatively small postflood discharges from an active cutbank on the east abutment of the sewer line crossing.

RECOMMENDATIONS FOR FUTURE STUDIES

The geomorphic and hydrologic complexity of stream systems in the semiarid West does not lend itself to the flood hazard regulatory practices established at the national level. The nature and pattern of damages in the 1983 flood confirm this conclusion. We recommend the following areas of research to improve the scientific basis for flood hazard regulation in these regions:

1. A method of flood-frequency analysis must be developed for a statistical series of peak flow records that violate assumption of a stationary mean. Regional hydroclimatological studies and paleohydrological studies of recent flood deposits may be promising approaches in this research.

FIGURE 38 Flood debris in the channel of Pantano Wash from the Rincon Country mobile home development (see Figure 26) in late October 1983. The view is downstream (north). Photograph by Peter Kresan.

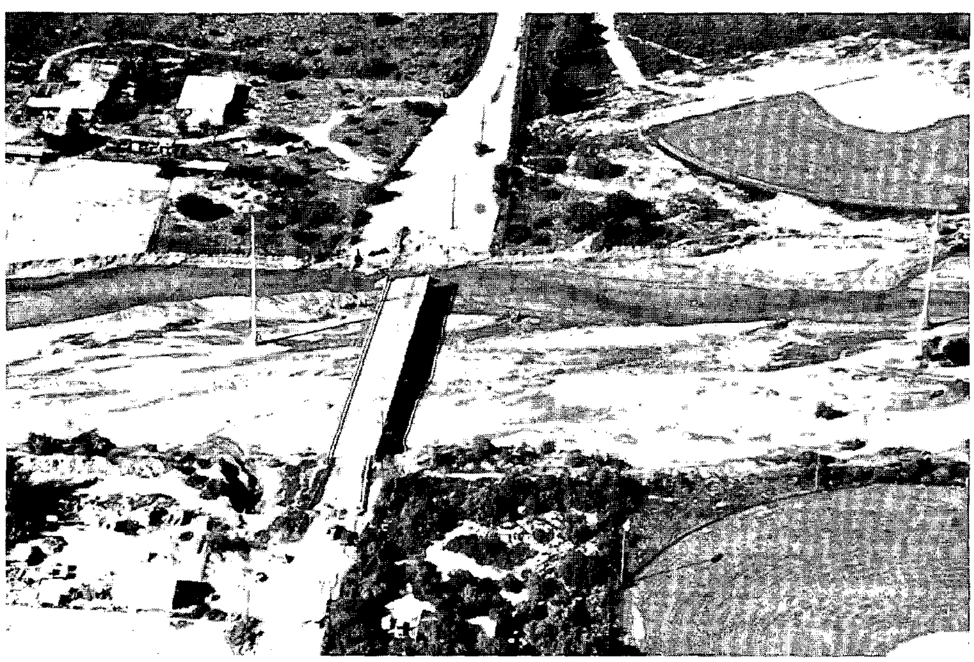


FIGURE 39 Dodge Road bridge on October 8, 1983, showing erosion of its north abutment by the Rillito. A ground photograph of the bridge is shown in Figure 40. Photograph by V. R. Baker.

TABLE 6 Selected Observations of Bridge Damages from the 1983 Tucson Flood

Stream	Bridge	Observations
Santa Cruz	Northbound Interstate 19	Riprap bank protection failed to prevent erosion of north abutment, resulting in the loss of about 60 m of the northbound approach lane (Figure 17).
Santa Cruz	San Xavier Road bridge at Martinez Hill	About 200 m of preflood riprap revetment on the west bank failed to prevent erosion of the west bridge abutment. Approximately 30 m of bank recession occurred in an active meander bend (Figure 17).
Santa Cruz	Valencia Road	Bank erosion of 10 m threatened to destroy the west abutment, but artificial filling during the flood prevented this. Bank erosion occurred despite a riprap revetment because scour undermined this protection.
Santa Cruz	Grant Road bridge	The west abutment was damaged by the westward migration of a meander cut slope. An old landfill upstream of the bridge was also exposed in this meander bend.
Santa Cruz	Sunset Road bridge	Total destruction.
Santa Cruz	Ina Road bridge	The west abutment was scoured despite preflood protection with a riprap revetment (Figure 21).
Santa Cruz	Cortaro Road bridge	Total destruction despite preflood protection with a wire-fence revetment.
Rillito	Swan Road	The north abutment was eroded by the cutbank of a meander.
Rillito	Dodge Road	The north abutment was eroded by the cutbank of a meander (Figures 27, 39, and 40).
Rillito	Campbell Avenue	Damage to the north abutment occurred despite a wire-fence and riprap revetment.
Rillito	First Avenue	The north abutment was eroded by the cutbank of a meander (Figure 28).

FIGURE 40 The Rillito at Dodge Road on October 5, 1983, showing the erosion of the north abutment. Photograph by Peter Kresan.

2. The complex regime behavior of semiarid streams must be incorporated into the analysis of channel behavior during flood events. This involves an appreciation, through geomorphic research, of the channel changes that occur in semiarid streams over a time scale of decades to centuries.

3. A total-system approach needs to be developed for the management of ephemeral stream courses in urban areas. This approach needs to establish the sediment budget responsible for regime adjustments. It also needs to establish the influence of urban land-use changes on both runoff and sediment yield to the stream courses.

4. Bank protective works, either piecemeal or continuous, need to be evaluated for their effects on the total stream system.

4

THE HUMAN RESPONSE TO THE OCTOBER 1983 FLOOD IN TUCSON

When the October 1983 flood hit Tucson, it caught local officials by surprise. Many of those with responsibilities in an emergency were out of town that first weekend of October. Those present soon found themselves in a chaotic disaster situation for which they were poorly prepared. Although individuals and groups responded well, there was an overall lack of coordination and communication that indicated a want of emergency planning and practice.

This chapter briefly describes the emergency response and attempts to explain why the community was caught off-guard. The explanation in turn examines two major factors: the public perception of the flood hazard, and community attitudes toward long-term planning. These perceptions and attitudes arise from the unique qualities of the desert environment and the atmosphere of rapid growth that has marked Tucson for the past several decades. Whether the flood of October 1983 will result in better emergency responses and more enlightened long-term planning is the subject of the final section.

THE EMERGENCY RESPONSE TO THE TUCSON FLOOD OF OCTOBER 1983

The emergency response to the Tucson flood of October 1983 showed the familiar signs of a lack of thorough emergency preparation. The flood arrived before most people realized its magnitude; timely warnings to the public were often not forthcoming; communication channels became jammed; good contact with the field was often unavailable; there was a lack of coordination among the various agencies involved; and a lack of trained emergency personnel to relieve regular staff soon became apparent (Pima County Manager's Office, 1983).

A major part of the problem can be attributed to a failure to take the flood hazard seriously. There was little or no regular practice of emergency procedures before the flood. Therefore problems were not anticipated or prepared for, proper equipment was not available, and tasks were not assigned to particular individuals or agencies.

Pima County Emergency Services is an organization with a tiny staff and small budget. Since the agency's main emphasis is on nuclear preparedness or chemical spills on Interstate 10, it devoted little time or energy to preparing for floods. Sporadic efforts in the past to organize meetings to discuss flood preparedness had failed because of a lack of interest, a lack of high priority, and a lack of leadership. The agency's Emergency Operating Center did not become the focus of the flood emergency response because other local and state agencies worked independently, using their own facilities with no apparent awareness of the great advantages in dealing with a disaster through a single emergency operating center. The lack of preparedness drills left each local agency without a clear idea of the roles of other agencies and of how to properly coordinate emergency response efforts.

The Pima County Sheriff's Department, which has major emergency responsibilities, is an example. The department worked independently out of their own facilities, which are far removed from the Emergency Operating Center. Each of the department's rural and urban districts also worked independently under a lieutenant. They did the tasks that they have been trained to do, such as getting barriers on bridges and highways, search and rescue, crowd control on arroyos, and evacuation as the need for it became apparent. A major concern of the Sheriff's Department was looting. The department was surprised to learn that very little took place. As in many previous disasters, much looting was expected and it turned out to be very rare in the emergency period.

Coordination and communication of information became a problem. Well-organized and experienced volunteer agencies such as the Red Cross were handicapped by a lack of good information. As Chapter 2 notes, the National Weather Service provided good information, but it was not used effectively at the local level. For example, in spite of the flood disaster, the Emergency Broadcast System was not activated, and thus, as Williams (1983) observes, "On Saturday, as the rivers rose and buildings fell, recorded music, network talk shows, sports events, and cartoons played on as if nothing was wrong."

This largely negative assessment of the local emergency response should be balanced by acknowledging that Tucsonans, like most people in disaster situations, did respond well as individuals and in agencies or departments. There was great willingness to pitch in and help, and many individuals and groups participated courageously and steadfastly. Two rescuers died in the line of duty when their helicopter crashed during rescue operations. The Red Cross did an excellent job of setting up emergency shelters for flood victims and coordinating the flow of blankets, clothing, and food. Many local government employees worked long hours at necessary tasks, and hordes of volunteers showed up to help. The major problem was the lack of overall coordination to use these energies effectively and of timely action to ensure a prompt response to all problems wherever they might be. The following two sections examine the reasons for this lack of a well-coordinated response.

PUBLIC PERCEPTION OF THE FLOOD HAZARD

Large, rare flood events are difficult to deal with anywhere. People find it hard to imagine the volume of water that will fill their local stream in a 50-, 100-, or 200-year flood because it is so far beyond the normal events they have personally experienced. In Tucson this general tendency to discount the possibility of large floods seems even more extreme. The arroyos, dry washes, and riverbeds in Tucson are dry over 300 days per year. Also, most Tucsonans are newcomers. Since the Santa Cruz has had fewer large flows over the past couple decades than have most nearby comparable basins, most Tucsonans have had little direct local flood experience.

The dry and sunny daily weather and dry washes in Tucson apparently lead newcomers and oldtimers alike to discount the flood hazard. On the few days each year when water flows, it is often only a few feet deep, hardly menacing at the bottom of the deeply entrenched steep-walled channels. Flash floods are typical. They rise quickly, recede quickly, and are quickly forgotten. "The floods are forgotten as soon as the sun comes out," said one county deputy sheriff to explain why the size and persistence of the October 1983 flood caught them by surprise. The rivers are so dry that local folklore has a category of "dry river jokes." This is exemplified by the recently established, annual "Rillito River Regatta," which features a parade of sand vehicles dressed up to look like watercraft (Hatfield, 1982).

Tucson has suffered many severe floods since being founded, and human intervention in the landscape has led to enormous changes in the river bottoms (Dobyns, 1981; Betancourt and Turner, in press). The irrigated agricultural landscape of the late Mexican and early Anglo period was totally transformed during floods in the 1890s, when the channel of the Santa Cruz at Tucson was entrenched. About 25 years later another devastating flood destroyed the Congress Street bridge, with lateral erosion there widening the channel to twice its former width. Photographs such as that in Figure 41 show huge crowds watching the flood. The convergence phenomenon was evident then just as in 1983, when huge crowds watched the turbulent water.

The flood of 1914-15 was not exceeded until the 1960s, so it is not surprising that the community's memory of major floods faded. People who were 20 or older when they saw that flood would be past retirement age before another flood of equal magnitude occurred. Even if they remained in the community, their numbers would have been swamped by the hundreds of thousands who arrived later with no knowledge of such large local floods.

The rapid growth of Tucson over the past four decades (Bufkin, 1981) has produced a population largely inexperienced with the desert (Saarinen, 1983) and local flooding conditions. Their images of floodplains derived from more humid parts of the country do not adequately describe the behavior of desert streams. Even professionals who are well informed about local hydrologic conditions are outnumbered by new arrivals who apply principles derived from other places. A shortage of well-trained personnel is evident and understandable, since even current hydrologic textbooks devote very little space to desert streams.

The first floodplain zoning ordinance applied in Tucson was based on the standard U.S. model, which is based primarily on overbank floods rather than lateral erosion. (See Bond (1984) for other problems related to use of national models in the Arizona context.) It took another decade of struggle before lateral erosion provisions were

FIGURE 41 Huge crowds watch 1914-15 flood. Source: Special Collections, University of Arizona Library.

included in local floodplain zoning ordinances. Many individuals and groups made concerted efforts, against strong resistance, to raise the level of concern about the flood hazard (Tellman et al., 1980).

Local newspaper coverage of pertinent past flood events could partially remedy the lack of direct local experience with floods. At the time of the floods in the 1890s and in 1914-15, the newspaper offices were within a few blocks of the river. Reporters, editors, and all other newspaper personnel had direct contact with the natural events. The coverage was extensive. Today's newspaper offices are much farther from the river, and writers or editors are little aware of the rich archival sources in their own files that could provide perspectives on flooding for the public. The special report on "The Flood of '83" put out by the Arizona Daily Star on October 17, 1983 (Beal, 1983), did a good job of documenting some of the damages from the flood. But it failed to provide the public with any perspective on how often such floods might occur or what the community should do to prepare for them.

Occasional editorials (Arizona Daily Star, 1981) or articles (Emerine, 1983) take a long-term planning perspective toward floodplain development. These are offset by others that strongly oppose floodplain planning measures. The prodevelopment stance of one newspaper editor was carried to extreme lengths in an editorial entitled "City Flood Plan More Dangerous Than Flood Threat" (Tucson Daily Citizen, 1976). The editorial downplayed the possibility of a severe storm, advocated a more flexible ordinance, and raised the fear that Tucsonans might be "flood proofed into the poorhouse." The quotation at the beginning of Chapter 1 of this report by the Metropolitan Tucson Convention and Visitor's Bureau (1983) provides another negative example of community leadership with respect to the flood hazard.

Public awareness and concern about the flood hazard in Tucson are very low. A study carried out by McPherson and Saarinen (1977) documented this low level of awareness and concern through interviews with residents living in the floodplain. The interviews revealed that over 60 percent of these floodplain dwellers did not realize that their areas were in a flood danger zone. Only 38 percent felt that they would be personally affected by a major flood. In 1978, shortly after the McPherson and Saarinen study was published, a major flood occurred on the Santa Cruz River. The U.S. Army Corps of Engineers was then carrying out some studies in Tucson, and the Corps supported a study to interview residents in the Santa Cruz floodplain using the McPherson and Saarinen questionnaire (Kemmeries, 1978). This provided a direct test of the effect of the 1978 flood on people's perceptions of personal risk. In the Kemmeries study only 9 percent perceived a personal risk, compared with 38 percent in the previous study. Since most people were spared any direct damage, they apparently felt this meant that they would be spared again in the future. Similar comments were elicited in informal interviewing of floodplain residents by a reporter from the Tucson Citizen just after the October 1983 flood (Davis, 1983). The findings of these studies are corroborated by the small number of flood insurance policies that have been purchased in areas of risk (Arizona Daily Star, 1983).

The local lack of awareness and concern about the flood hazard helps explain why Tucson was unprepared for the October 1983 flood. But to fully understand the local adaptation to the flood hazard, one must also take into account general community attitudes toward long-term planning.

COMMUNITY ATTITUDES TOWARD LONG-TERM PLANNING

The phenomenal growth of Tucson during the past four decades has produced a prosperous economic climate and has attracted many people who wish to profit from that climate. It has also led to some concern regarding the deleterious social and environmental consequences of rapid growth. A recent study (Planning and Management Consultants, 1980) based on interviews of Tucson community leaders concluded that "the dominant ideology in the community remains the traditional Arizona one of unfettered growth; it is equated with freedom and the American way (p. E-10)." Although seen as the dominant ideology, this view has never been totally accepted and continues to be challenged (Abbey, 1984).

In the early 1970s Tucson went through a strong local debate on the merits of controlled or managed growth. Many environmental activists were linked with the controlled-growth side of the issue, and for a time local politics were dominated by people with this view. The Tucson Comprehensive Plan of 1975 (City of Tucson, 1975) clearly reflects the controlled-growth view. It is interesting to note that a series of volumes published by the Urban Land Institute in 1975 under the title Management and Control of Growth includes both pro and con positions taken by Tucsonans at the time (Finkler, 1975; Drachman, 1975).

Local developers vigorously opposed growth management. Most of the environmentally oriented city council was voted out of office in a recall election for the political mistake of raising the water rates during the summer when water use was at a peak, and their views were discredited. Currently, the progrowth forces, which are led by developers who have an obvious stake in this position, have the ascendancy. In the recent mayoralty contest, the progrowth, prodevelopment incumbent won a fourth successive four-year term, but ironically the majority of the council is of the opposing party. The strength of feelings on both sides has impeded discussion that could lead to wise decision making. It is a local dilemma that stymies initiatives by either side.

The history of floodplain zoning in Tucson clearly illustrates the strong resistance of local landowners and developers to land-use controls, as well as the general lack of awareness of flood-related issues by the population. It is not simply a matter of people not realizing that building in floodplains can be dangerous and expensive. Throughout its history there have been Tucsonans who have learned by experiencing floods. Before the entrenchment of the Santa Cruz, even minor floods would cover much of the low-lying land in the valley, and a newspaper report of 1886 stated that "the bottom of the Santa Cruz Valley is an unsafe place for dwelling houses" (Betancourt and Turner, in press). Presumably, others shared this view, since most development was on the terraces above the valley floor. Still, even then there were some who built houses in the valley bottom.

The earliest attempt to regulate development on the floodplain aroused considerable wrath among local landowners. The two planners who suggested it were hanged in effigy in 1963 in front of the Elks' Club where a public hearing was to take place. The first paragraph of a report in the Tucson Daily Citizen (Cooper, 1963) described the scene:

> Some 400 irate landowners and residents along the Rillito River today swarmed over a floodplain ordinance hearing, hanged two city-county officials in effigy and made one common point clear: They are violently opposed to restrictive zoning.

There were threats of even worse treatment (Faure, 1981).

Real progress in developing floodplain zoning did not occur in Tucson until the federal government exerted pressure at the state and local levels. For many decades the federal government had pursued the policy of building dams and levees to protect the public from floods. This policy was not successful, as flood losses continued to grow despite billions of dollars spent on flood protective structures. Ironically, the building of large, expensive protective works often helped to increase the damages of the large, rare floods, because of what has been termed the "levee effect." Once levees were built, people assumed that formerly risky areas were now safe and moved into them. Thus when a large, rare flood brought waters beyond the capacity of the flood protective works, floodwaters wreaked havoc on a much larger population.

The new federal policy involved the carrot of flood insurance and the stick of floodplain regulation. Flood insurance would be available for any community that adopted floodplain regulations. These policies reached Tucson in 1972, when the State of Arizona began passing flood control legislation. The local government felt obligated to act, because by making it impossible to obtain the needed insurance, the city could be sued by someone suffering flood damages on the grounds that the city failed to act.

As a result of state and federal pressure, both the City of Tucson and Pima County developed floodplain zoning ordinances. Pima County's ordinance was regarded as a weak one with many loopholes and no real teeth. It was adopted in 1974. The City of Tucson, with its environmentally oriented city council, was developing a much stronger ordinance, which many people expected might later be adopted by the county (City of Tucson Department of Planning, 1976). This proposed ordinance, which contained provisions to deal with bank erosion on meanders, got through the Citizen's Advisory Planning Commission. But it was never adopted by the city council after most of the council's members were ousted from office through the recall election. The city did not adopt a strong floodplain ordinance. In fact, it did not adopt any floodplain ordinance until federal pressure was once again applied.

The new federal pressure came from the completion of the local floodplain mapping based on fixed bed models. At this point the city was no longer eligible for flood insurance with only the intention of adopting an ordinance. It now had to adopt an ordinance to remain eligible for flood insurance. The state, too, which was providing funds for the downtown Rio Nuevo project, required that the city have an ordinance. In July 1980 the city therefore adopted a floodplain ordinance much like the weak version adopted earlier by Pima County. Even as it was adopted, the ordinance was seen as inadequate, and a committee was set up to develop a better one. However, it should be noted that the Pima County and City of Tucson ordinances, although not ideal, are considered the best and most strictly enforced floodplain ordinances in Arizona (Leslie A. Bond, personal communication, 1984).

The committee that was convened to develop a better floodplain ordinance consisted of a variety of citizens, from laymen to experts. Various city agencies were represented, as were the Southern Arizona Home Builders Association and the Tucson Board of Realtors. It soon became clear that the main battle was between the hydrologic experts (from the University of Arizona and Pima College, the U.S. Geological Survey, and the Corps of Engineers) and the home builders' representative. A compromise document was passed on to the council. The council sent it back for further revisions due to strong pressure from builders and real estate agents. When a less restrictive version returned from the committee, the builders and realtors still objected. In a newspaper article entitled "Diluted Flood Plain Law Likely," Burchell (1983) stated that, "In the two most recent council discussions of the proposal, it was amended four times at the request of the development industry."

A measure of the degree of dilution of the original proposals may be seen in the fate of the setback provision. One committee member felt that no building should be allowed within 1,000 ft of the banks because lateral erosion of that magnitude had occurred in the past. The developers wanted no setback. Getting a lateral erosion provision was an accomplishment in itself. But by the time the provision appeared in the ordinance adopted in 1982, the limit was only 300 ft for residential buildings and 100 ft for commercial and industrial developments. One person interviewed pointed out that such compromises were a great step forward from previous periods when only two extreme viewpoints existed: those who advocated no building whatever in floodplains, and those who said that the government should stay clear of the floodway and let the buyer beware.

PIECEMEAL PLANNING IN FLOOD PLAINS

Past planning for floodplains in Tucson can best be described as piecemeal. The history of floodplain zoning indicates that different jurisdictions have used different design standards at different times. The design standards of the 1960s differed from those of the 1970s, which also differed from those of the 1980s.

Many of the areas of major damage in the October flood were developed in conformance with past codes. The Lamar Heights area was built up before floodplain zoning was established (Figures 18 and 42). The Pima Park Townhomes (Figure 31) on the Rillito near Prince Road were built with densities derived from earlier zoning.

An exception was the damaged Riverfront Village executive offices on North First Avenue (Figures 35 and 36), which were built at the insistence of the developer despite their nonconformance with zoning standards and the danger from floods. The developer was allowed to build them after signing the following release statement (Pima County Recorder, 1983):

> We, the undersigned, our successors and assigns, do hereby save Pima County and the City of Tucson, their successors and assigns, their employees, officers, and agents, harmless from any and all claims for damages related to the use of said lands now and in the future by reason of flooding, flowage, erosion or damage caused by water, whether surface, flood or rainfall.

A major difficulty in planning for the river as a system is that most of the floodplain land in the Pima County portions of Tucson is privately owned. The threat of suits by property owners may be enough to gain them some variance. This does not mean that the city and county cannot legislate the land use, but it does leave open the possibility of suits that would leave the interpretation to the courts. National decisions on environmental issues and a recent local court case involving a streambed gravel pit mining operation (*Pima County* v. *John Cardi*, 1979) indicate that the owners' wishes may not prevail when a hazard to life and property is involved.

Private ownership of the river leads to decisions being made on a plot-by-plot basis. Developers, who are engaged in a risky business

FIGURE 42 Aerial view of Lamar Heights on October 2, 1983. Notice that the junction of Michigan and Koster avenues has been eroded away along with several houses. Photograph by Peter Kresan.

with a rather short-term time horizon, are inclined to disregard such long-term hazards as floods, which may occur long after they have left the scene. They prefer to avoid the extra costs of flood-proofing or flood-protection and are likely to discount the flood hazard, as the case of the Riverfront Village offices demonstrates. Furthermore, even if individual developments did provide bank protection, these would only enhance erosion immediately downstream (as demonstrated in Chapter 3 and shown in Figure 43).

Another factor contributing to the piecemeal planning of the past is a holdover of small-town attitudes toward dealing with desert floods and rainfall. A casual attitude toward floods and rainstorms is evident in the public works designed to handle flows of water. Dip crossings are common (Figure 44), and in spite of warning signs people try to ford them during floods, sometimes paying for the mistake with their lives. One substandard road crossing the bed of the Santa Cruz River was closed by the October 1983 flood, isolating a subdivision south of Tucson for five days. In the absence of storm sewers, certain streets handle the

FIGURE 43 Aerial view of Santa Cruz River showing the sudden widening of the stream banks at a point with no bank protection. Photograph by Peter Kresan.

runoff and become, in effect, tributaries of major streams when enough rain falls. Each year after a major storm, pictures appear in the paper joking about how people adapt to these conditions by pulling out their water skis, inner tubes, or boats (Figure 45).

FIGURE 44 Dip crossing showing common practice of roads crossing at streambed level. Photograph by Thomas F. Saarinen.

FIGURE 45 Youths on water skis after a rainstorm. Source: Arizona Daily Star.

This small-town atmosphere is not as acceptable today as it once was. Higher road and runoff standards are being demanded by the public and are necessary in a city rapidly approaching a population of a half million. The costly delays of tens of thousands of people by runoff or increased chances of accidents can no longer be laughed off as minor inconveniences. Sheriffs, police officers, and others often find the problems of high flows in streets frustrating, inconvenient, and unsafe. A channel more than a foot deep may force lengthy detours. As more and more people arrive, the need for a more sensitive adaptation to the desert environment intensifies, not just with respect to the main streams but throughout the newly urbanized environment.

As noted in Chapter 3, the ecosystem around Tucson has undergone dramatic physical changes. Since the 1950s, the rate of removal of groundwater (the sole water supply for Tucson) has exceeded the natural rate of replenishment (Barr and Pingery, 1976). As a result, the water table has been dropping at a rate that accelerates each year as the base population continues to grow rapidly. The falling water table has adversely affected the amount of riparian vegetation, which if present would slow floodflows somewhat and contribute to the deposition of sediments. The vast stretches of formerly open desert that are now covered by houses, buildings, streets, roads, and other paved areas leads to more rapid runoff with less sediment, thus enhancing the erosive power of the rivers. Gravel, sand, and other sediment have been mined for construction materials to build homes, roads, and other buildings, as well as to provide fill for the major freeway, which parallels the river's course for many miles through the city. Furthermore, major streets like River Road and Mission Lane trap most of the sediment that formerly would wash down from the mountains to replenish the sediment carried away by the rivers.

These human-induced changes to the ecosystem have occurred with little heed to their potential consequences. Yet in a river or any natural system, a change anywhere will reverberate throughout the system. It is therefore important to try to elucidate some of the repercussions caused by human alterations of the natural landscape. This can make it easier to avoid the unforeseen deleterious effects that occurred in the Tucson flood of October 1983 and will occur in future flood events.

Adaptation to the local ecosystem is not needed only in the main streams. It is necessary through the entire system of tributary washes. Table 7 lists the probabilities of storms of various sizes centering on small areas anywhere in Tucson's urbanized areas. These can and do have devastating effects on small localities if the infrastructure of pipes, conduits, and stream channels is inadequate (Reich, 1982). Therefore local adaptations to the ecosystem, such as a detention-retention provision in the zoning ordinance designed to slow runoff and enhance on-site infiltration, should be sought and welcomed. Unfortunately, adoption of such innovations may take place only after a protracted struggle, and the longer they are delayed the more costly will be their implementation.

TABLE 7 Chance That Rainstorms Will Strike a City of 100 Square Miles

Size of Storm	Average Number of Strikes
200-year storm	2 strikes in 25 years
100-year storm	2 strikes in 10 years
50-year storm	2 strikes in 5 years
10-year storm	2 strikes in 1 year
5-year storm	4 strikes in 1 year
2-year storm	10 strikes in 1 year

Source: Reich, 1982.

FUTURE PROSPECTS FOR ENLIGHTENED FLOODPLAIN PLANNING IN TUCSON

Research on natural hazards often notes the tendency for people to adopt mitigation measures immediately after a major disaster. If not adopted then, the likelihood of adoption diminishes rapidly as the memory of the event fades. There was a willingness to do something about floodplain planning immediately after the Tucson flood of October 1983. The local floodplain managers were astute enough to take advantage of this short period of grace. As a result, on October 11, within a week of the flood, the Pima County Board of Supervisors voted to amend the floodplain ordinance, placing an 18-month moratorium on rezonings and construction in floodplains. Such an amendment would not have had a chance of passing earlier, according to the head of the Pima County Department of Transportation and Flood Control District (Bual, 1983).

The moratorium on rezonings and construction in floodplains gives Tucson officials and citizens an opportunity to once more think through the issue of floodplain management. The piecemeal planning of the past does not work, as the pattern of enhanced erosion just beyond protected areas demonstrates. The damage to public and private property along stream banks was great, but it is minor compared with what it could be given current construction plans in Tucson, particularly along the Rillito.

The Rillito corridor has been one of the most active areas of land speculation and development in the Tucson metropolitan area over the past several years. This is especially the case along the north bank, which is immediately adjacent to the Catalina foothills. This foothills area is widely perceived as the most attractive and prestigious location in Tucson. It has a spectacular mountain backdrop, wide vistas across the valley, rolling terrain, and large and dense stands of saguaro-palo verde desert vegetation. The desirability of the area has led to much development pressure and rising land values. Land at Campbell Avenue and River Road has the highest value in the corridor, but the entire area from Country Club Avenue to Oracle Road has been bid up very high.

High land costs lead to high-density use. So the Rillito corridor, formerly notable for its rural ambience with stables, ranches, the Rillito Race Track, and winding River Road (Figure 46), is now being transformed by high-density residential development (Figure 47). Over a thousand building units have been platted, and many would probably be under construction were it not for the moratorium. Locations adjacent to the river are reflected in such names as Haciendas de Rios, Rio Cancion, Riverside Apartments, River Grove Estates, Rio Vista, and Lazy Creek. Obviously the potential for flood damage will be much greater in the future as these and other projects are completed.

The success of soil-cement bank protection has been praised and seen by some as a solution to future flood erosion problems in Tucson (Cornelius, 1983). The most notable use of soil-cement bank protection was in the Rio Nuevo project west of downtown Tucson on the Santa Cruz River, where close to 2 miles of bank protection were in place prior to the October flood. But the cost of this project could be justified on a benefit-cost ratio because of its special character. It is a very large, long-term project designed to dovetail with downtown redevelopment and the Santa Cruz River Park (Figure 48). Major important bridges were already in place, and former landfill areas posed potential problems without adequate protection (Figure 49). Most projects would not have as compelling a set of reasons for such substantial public and private investment in bank protection and grade control structures. The Rio Nuevo project was also designed to meet FEMA design standards for the 100-year flood (850 m^3/s or 30,000 cfs). During the October flood the limits of its capacity were strained (Figure 50) and areas immediately downstream were severely eroded (Figure 51). To build protective works beyond this standard is enormously expensive.

Since piecemeal planning will not work, the question becomes whether to fully protect the river system or to leave it alone. Clearly it will be hard to leave it alone given the bridges already in place and current pressure toward development. In their recent studies, the Corps of Engineers essentially concluded that the value of current development in Tucson's floodplains did not warrant the costs of full bank protection, which, including land acquisition costs, may amount to $3 million per mile.

If Tucsonans insist on developing the floodplain, some hard thinking should be devoted to the question of who pays. One view expressed is that harvesting the floodplain should not be charged to people who locate elsewhere. Presumably those who benefit should share in the costs. It would be worthwhile to study carefully what the most equitable arrangement of cost sharing between public and private interests might be before proceeding further.

Meanwhile, as the memory of the October 1983 flood fades, the likelihood that appropriate mitigation measures will be adopted continues to diminish. Less than two months after the Tucson flood, a meeting to discuss its implications was organized by the Environment and Behavior Committee of the University of Arizona. Speaking at the meeting were the two top floodplain managers for the city and the county. A local

FIGURE 46 Low-density rural ambiance formerly characteristic of the entire Rillito corridor. On the left are homes, stables, and open fields. On the right is a tennis club; in the upper right background are the Pima Park Townhouses (see Figure 37). Photograph by Peter Kresan.

expert from the university was also there with slides of the changes in the river, as was the study team's leader with the team's preliminary findings. One might imagine that less than two months after the largest flood in the city's history, this meeting might have had great local interest, particularly when calculations on the recurrence interval of

FIGURE 47 New construction now characteristic of many portions of the Rillito corridor. Notice the Rillito Race Track in the background. Photograph by Thomas F. Saarinen.

the flood were being presented. Not so. Both local newspapers mentioned the event, but it merited only a tiny interior article in each.

The head of the Pima County Flood Control District, in his speech at this meeting, discussed the cycle of concern about floods. He said that the community was now in the postflood stage, meaning back to normal. As the newspaper coverage so clearly implied, the brief awakening to a perceived need for floodplain management was over.

On February 21, 1984, the voters of Pima County approved a $63.8 million bond election to repair flood damages. This indicated that the community was willing to pay for damages from the October flood. To what extent the community will support long-term future floodplain management remains an open question.

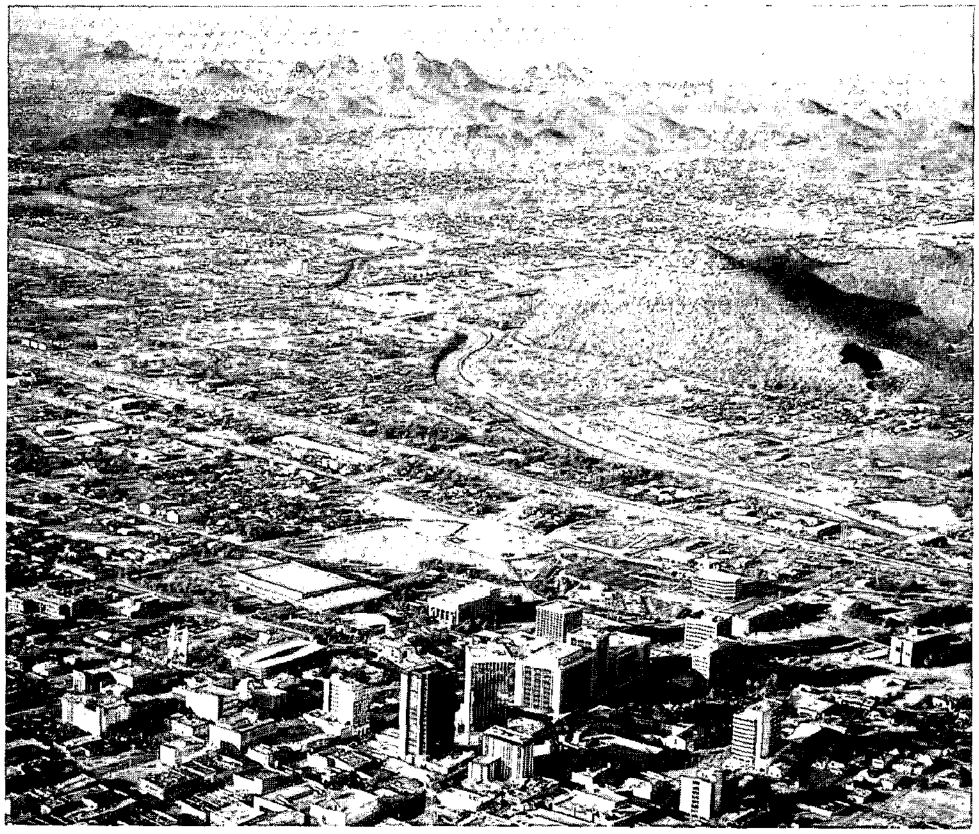


FIGURE 48 The relationship of the Rio Nuevo Project to the downtown is clearly shown in this view looking west across the Santa Cruz toward A Mountain with the Congress Street bridge in the middle right edge. Figure 49 shows a closer view of the project area. Photograph by Peter Kresan.

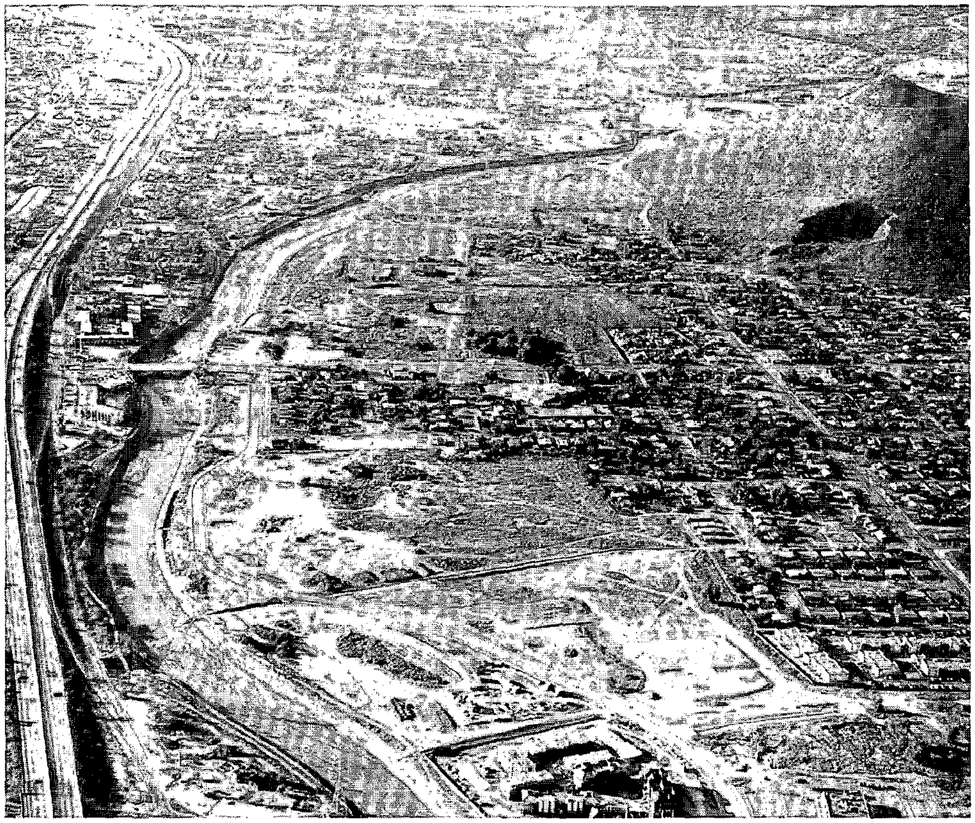


FIGURE 49 View looking south along the Santa Cruz with Interstate 10 on the left. The open, yet-to-be developed lands of the Rio Nuevo project are west of the Santa Cruz between the neighborhood of Menlo Park and the river. In the middle background is the Congress Street bridge. South of Congress is a large area of sanitary landfill. Just above the bottom edge of the photograph may be seen new construction of the first stage of the Rio Nuevo project at St. Mary's Road (also see Figure 50). Photograph by Peter Kresan.

FIGURE 50 The St. Mary's bridge during the flood of the Santa Cruz on October 2, 1983. Notice the waves above the level of the riverside walk. The new construction in the background is the first residential portion of the Rio Nuevo project. Photograph by Peter Kresan.

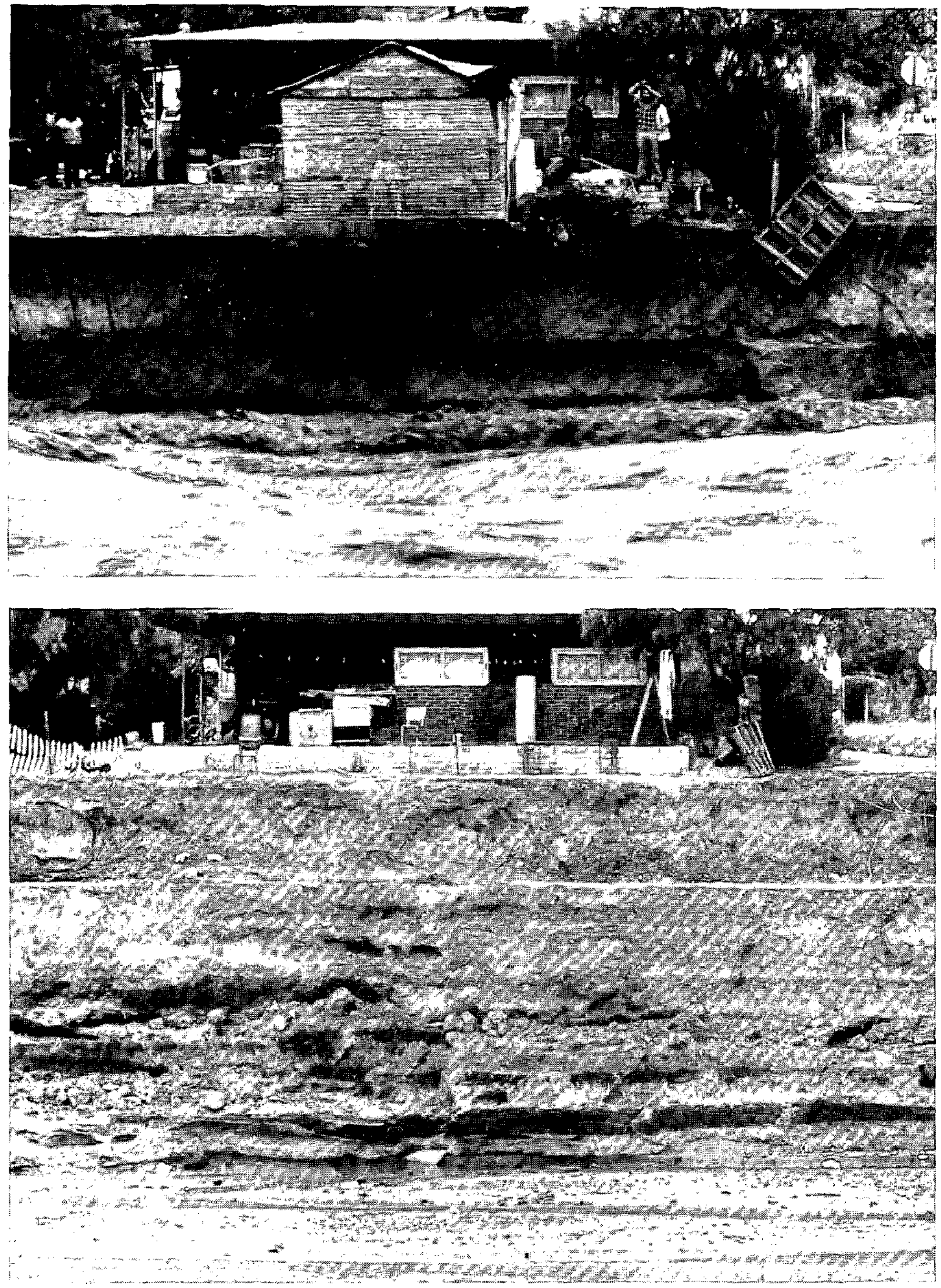


FIGURE 51 Point on the west bank of the Santa Cruz just beyond the bank protection of the Rio Nuevo project. The top photograph, taken during the flood on October 2, 1983, shows people watching the undermining of the bank below the shed. The bottom photograph, taken later in the month, shows that the portion of the bank on which the shed stood is no longer present. The view of the house is no longer obscured by the shed and the roots of the tree at right are exposed. Photograph by Peter Kresan.

5

CONCLUSIONS

The study team limited its study to the Tucson metropolitan area to focus on what it regarded as two important aspects of the event. The first was the way in which floods of desert streams differ from floods in humid areas, for which most floodplain legislation has been developed. The second was the implications of Tucson's rapid growth for dealing with the flood hazard.

The storm that caused the Tucson flood of October 1983 had a recurrence interval for a 24-hour period of 30 to 50 years. Soils were saturated prior to the flood by the third wettest August and the second wettest September of record. Problems arose in the gathering and communication of hydrologic information during the storm, and the dissemination of weather-related information to the public and emergency agencies was often inadequate. Agencies involved in disasters need to work together before, during, and after the event to coordinate their efforts, and the role of the National Weather Service in analyzing the event needs to be clearly defined.

The stream flows on the Santa Cruz River and the Rillito were the largest of record, though those on the Canada del Oro and Pantano were not. The record flow on the Santa Cruz was one of a series of high flows since the early 1960s. These can be interpreted as the result of an unusually wet series of years and human-induced changes in the natural system that have accentuated runoff. Certainly, within the Tucson metropolitan area, the desert has been significantly altered in ways that enhance stream flow. To be on the safe side, the community should design as if more high flows will be forthcoming.

The nature and pattern of damages and channel change during the 1983 flood demonstrate the profound geomorphic and hydrologic complexity of stream systems in the semiarid West. Nationally standardized procedures for flood-hazard evaluation proved inadequate for anticipating the damages. When the method developed by the U.S. Water Resources Council (1981) of determining floodflow frequency is applied to the Santa Cruz River for the period 1915-81, the 1983 flood discharge is predicted to have a return period greater than 1,000 years. The 1983 flood exceeded the 100-year flood magnitude of the Federal Emergency Management Agency (FEMA) by a factor of 1.75. However, these flood-frequency analyses appear to violate the assumption of a stationary mean, since the largest floods on the Santa Cruz occur in the most recent part of the flood series.

Even more problematic is the use of standard step-backwater calculations to route flood discharges obtained from the standard flood-frequency analyses. This procedure, as used in FEMA's 1982 Flood Insurance Study, assumes a static channel and valley floor geometry. So much channel enlargement occurred during the flooding that the FEMA study greatly overestimated areas of overbank flooding along many segments of the Santa Cruz. Standard hydraulic procedures simply do not apply to the complex sediment-charged stream systems of the semiarid West. The regime behavior of such streams must be incorporated into the analysis of channel behavior during flood events.

Within Tucson there was little overbank flow. The greatest flood damage was caused by lateral erosion of arroyo walls. This provides strong justification for the lateral erosion provision recently added to the local floodplain zoning ordinances. Lateral erosion severely damaged buildings adjacent to the streams and bridges, causing transportation problems and creating large expenses for the community.

Soil-cement bank protection, which has been used in several sections of the river system, held up well, but aerial photographs of flood damage reveal that this was at some expense to adjacent areas. A consistent location of lateral erosion was immediately downstream from places with strong bank protection. Piecemeal bank protection does not work. Clearly the rivers must be treated as a system. The areas along streams should either be left alone or completely protected.

Downstream from Tucson stream channels disappear. In this area of deposition from ephemeral streams, floodwaters spread over a wide area, moving as sheet flow with no permanent channel. Here the flood damaged agricultural land and human settlements, with the usual associated problems.

The Tucson flood has provided the community with a strong impetus to think carefully about future floodplain development. So far, only a limited amount of development has occurred in the flood-prone areas. But as open space close to the city has become more scarce due to rapid urban growth, pressure has built to develop the floodplain land, which is largely privately owned. In a community dominated by positive attitudes toward growth and development, it will be difficult to resist this pressure. Yet the costs of complete bank protection are prohibitive. Unless private developers in conjunction with public authorities can organize some sort of improvement district to pay the costs of protecting the entire river, it would be unwise for the community to allow them to proceed. Furthermore, if complete bank protection is provided, grade control structures will be needed to prevent downcutting that would undermine the protective works. The costs of these grade control structures might equal or exceed the cost of bank protection. But even if these enormous costs could be met, and Tucson were completely protected, what would happen to the areas downstream?

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APPENDIX A:

WEATHER MAPS FOR SEPTEMBER 28-OCTOBER 3, 1983

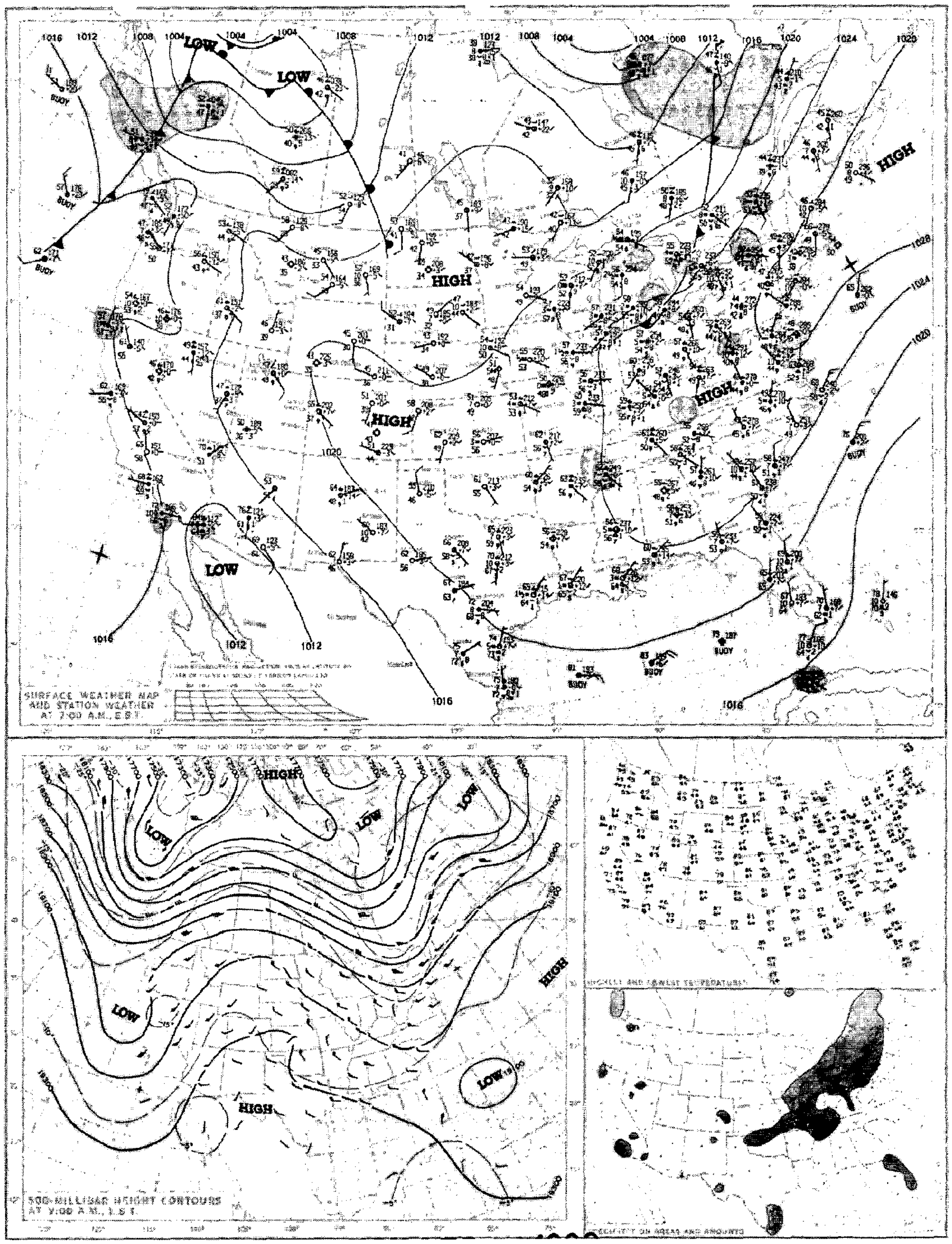


FIGURE A1 Meteorological conditions on Monday, September 26, 1983.

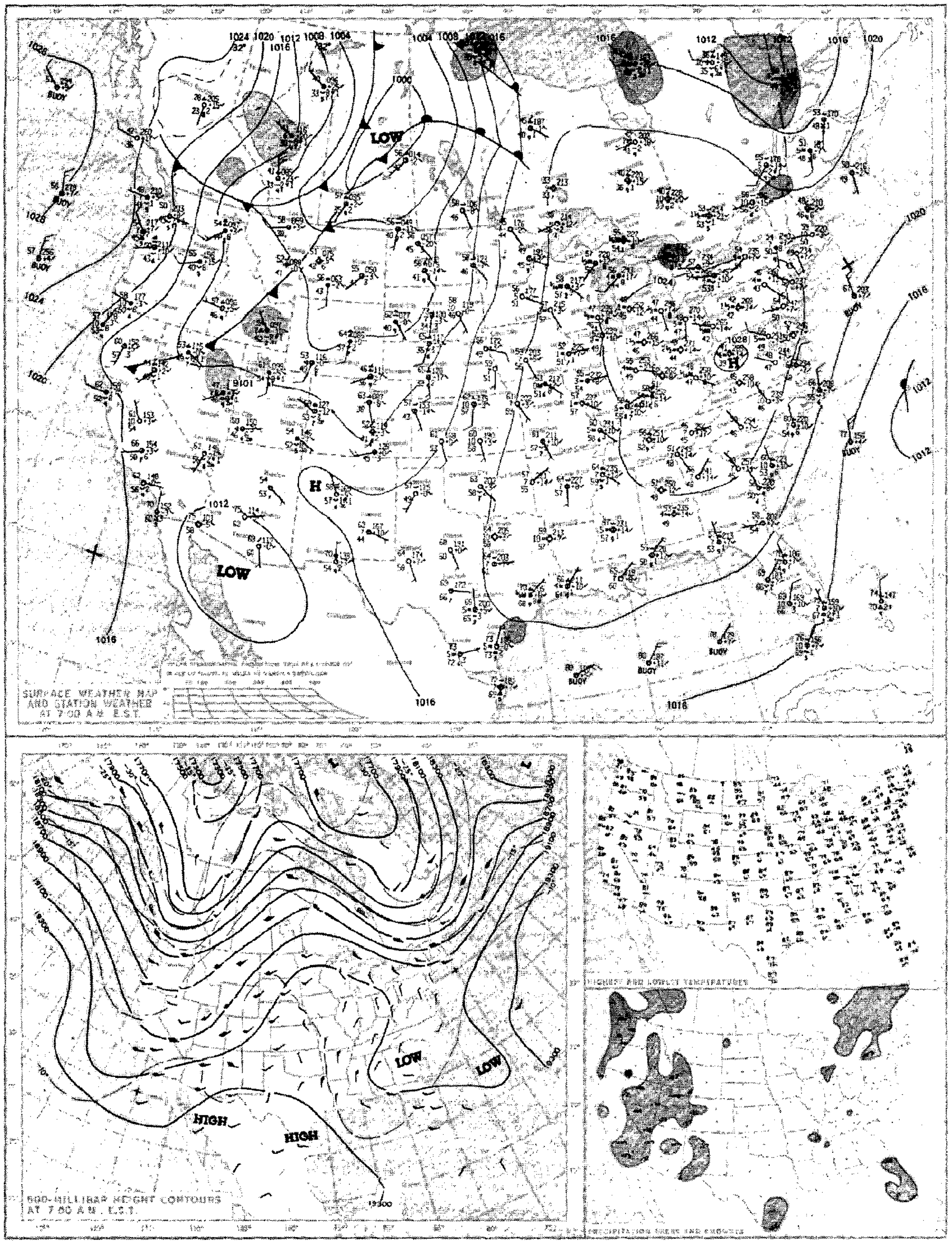


FIGURE A2 Meteorological conditions on Tuesday, September 27, 1983.

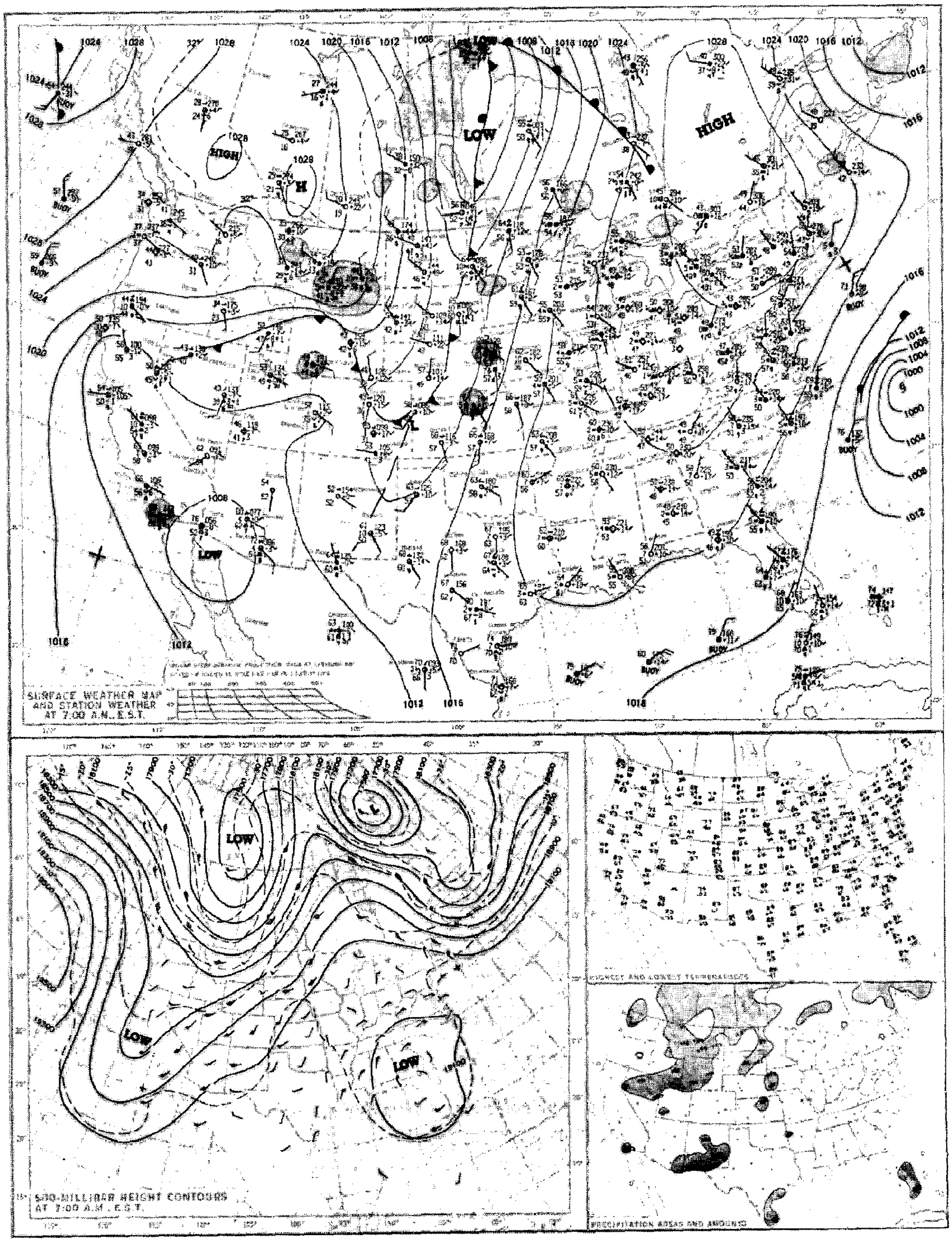


FIGURE A3 Meteorological conditions on Wednesday, September 28, 1983.

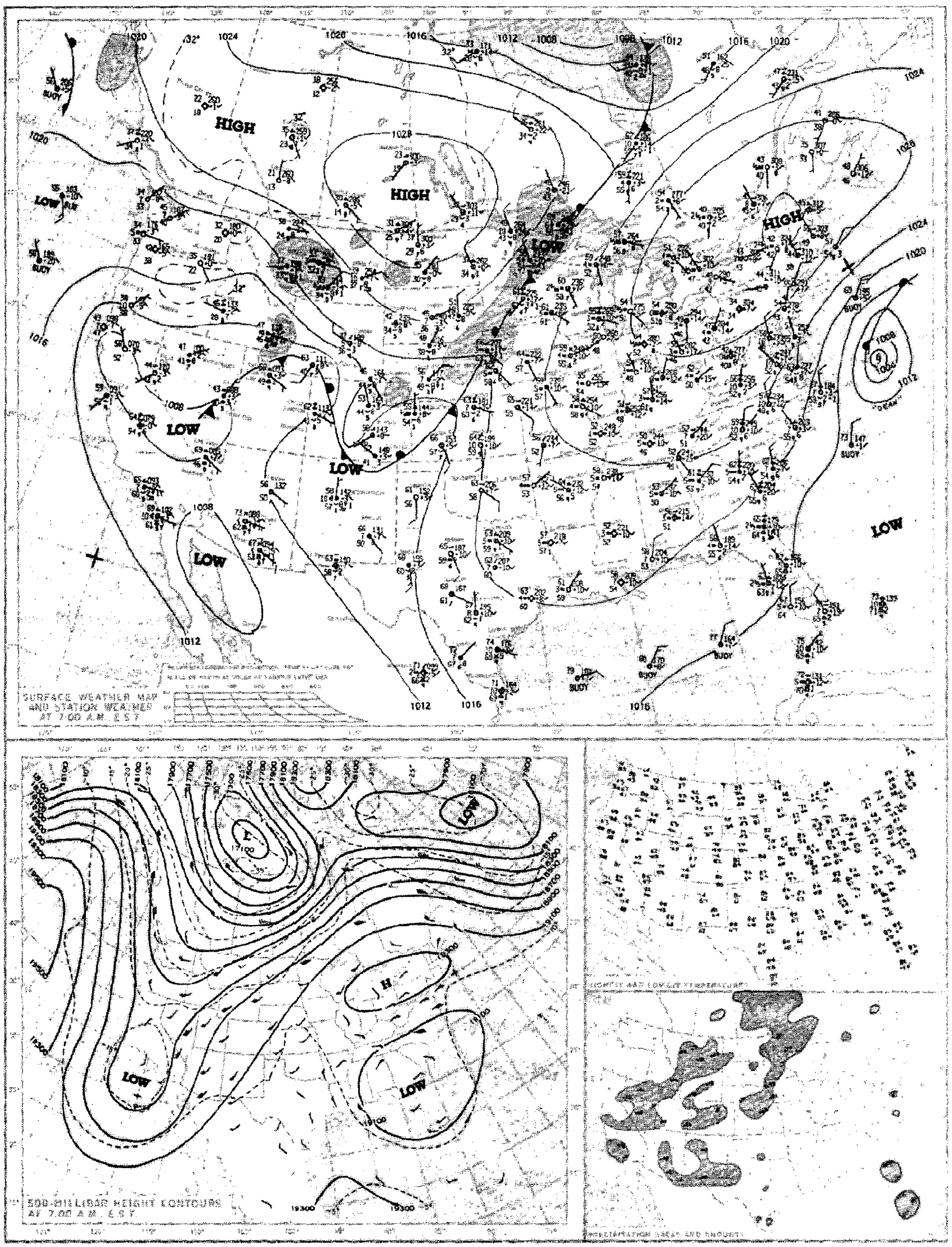


FIGURE A4 Meteorological conditions on Thursday, September 29, 1983.

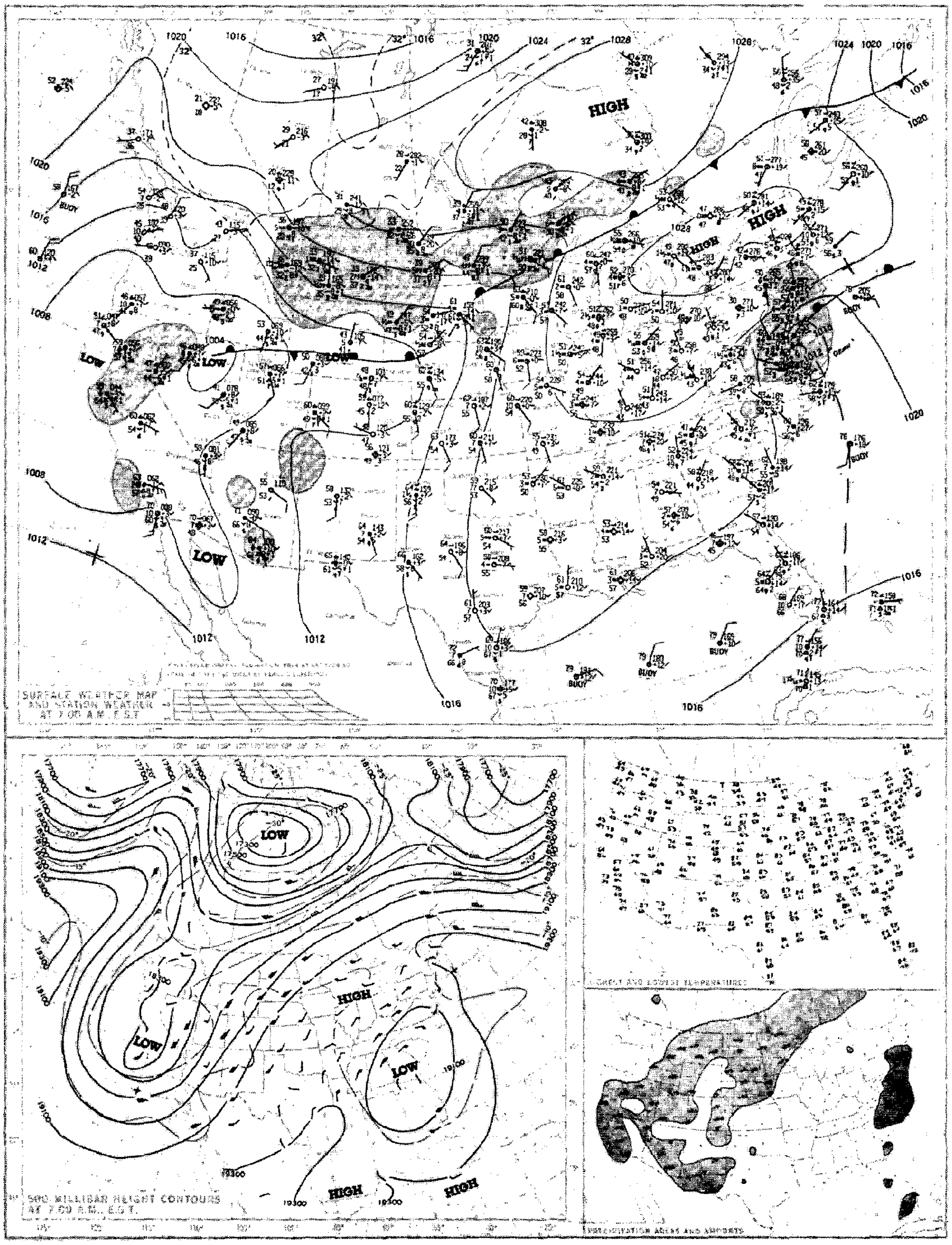


FIGURE A5 Meteorological conditions on Friday, September 30, 1983.

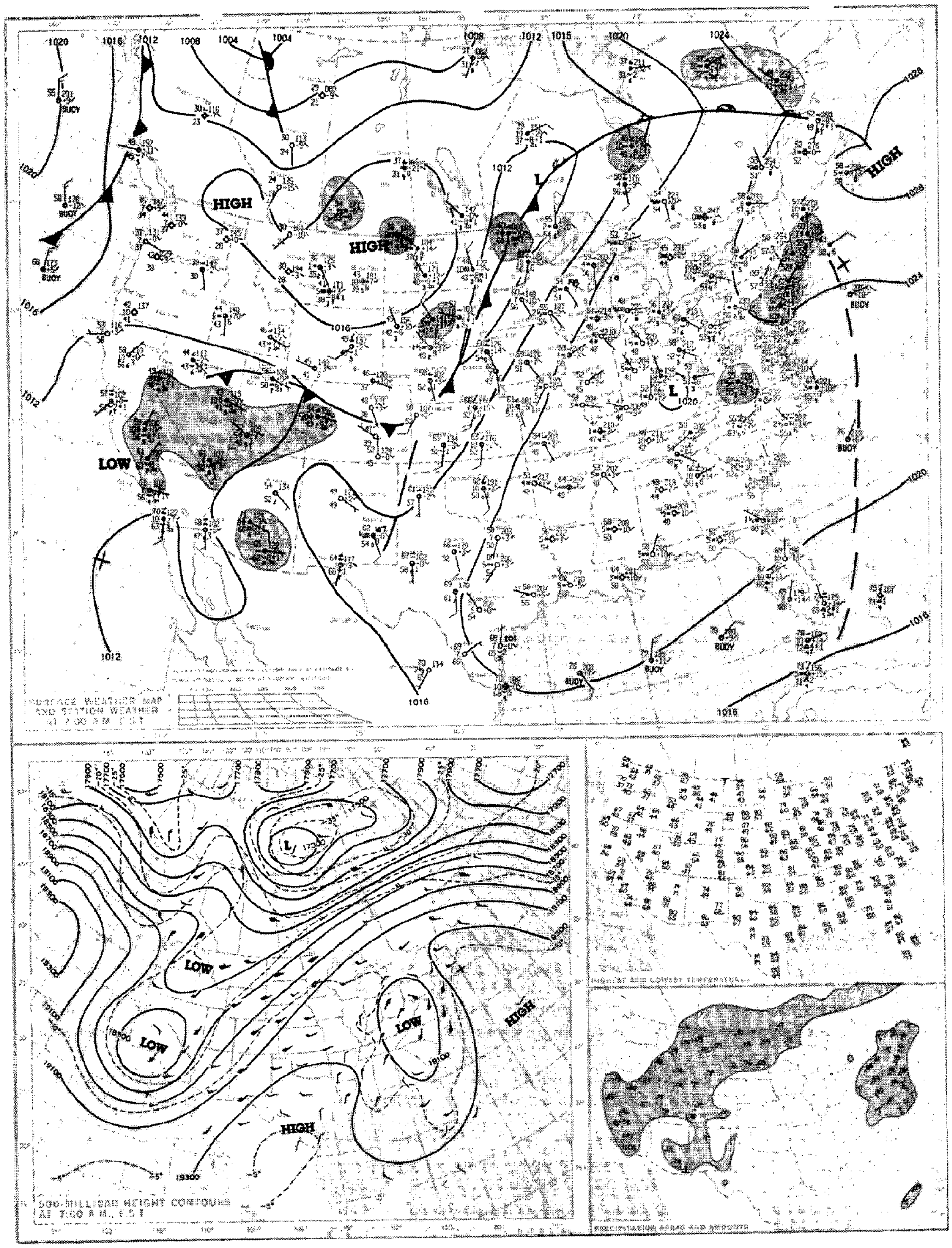


FIGURE A6 Meteorological conditions on Saturday, October 1, 1983.

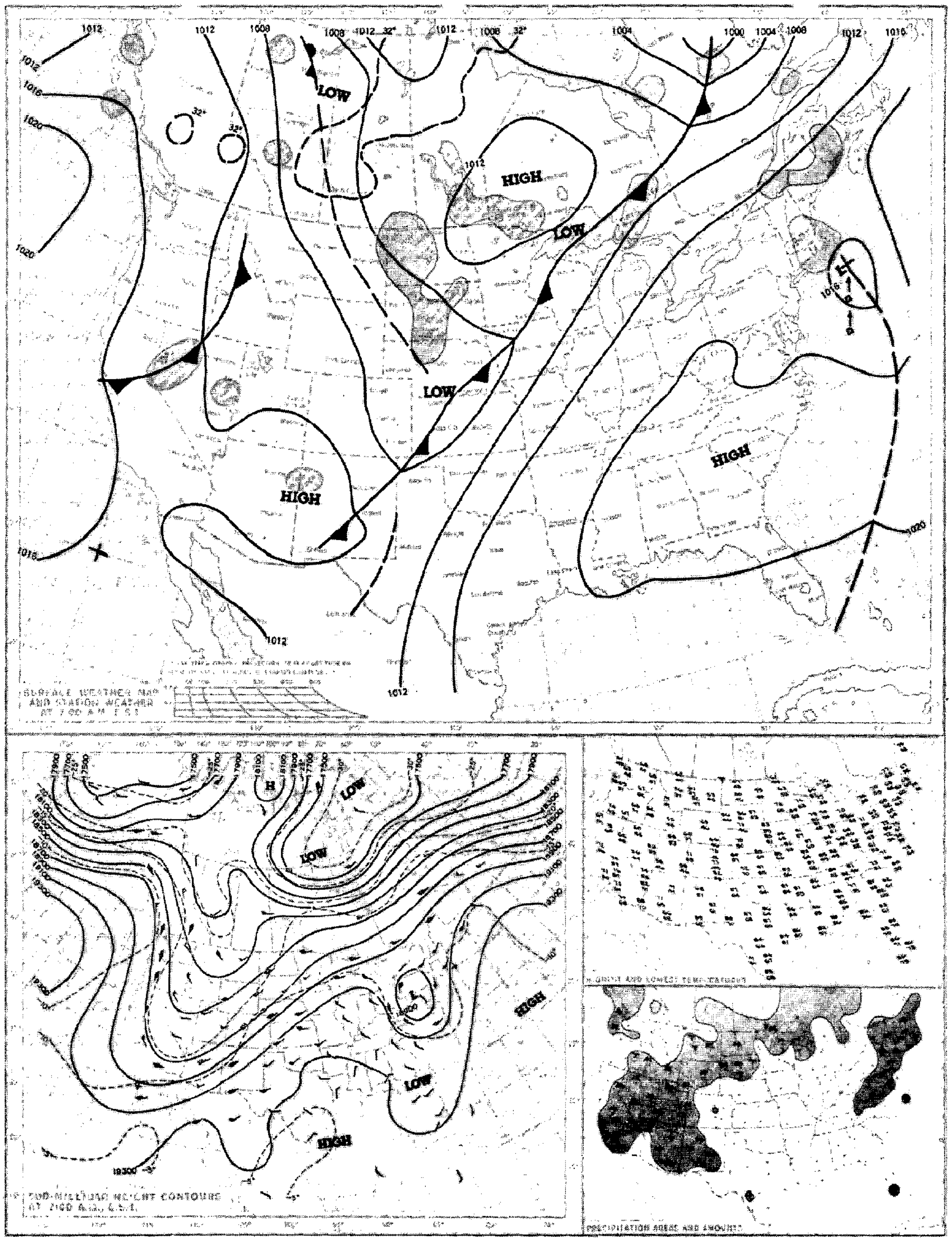


FIGURE A7 Meteorological conditions on Sunday, October 2, 1983.

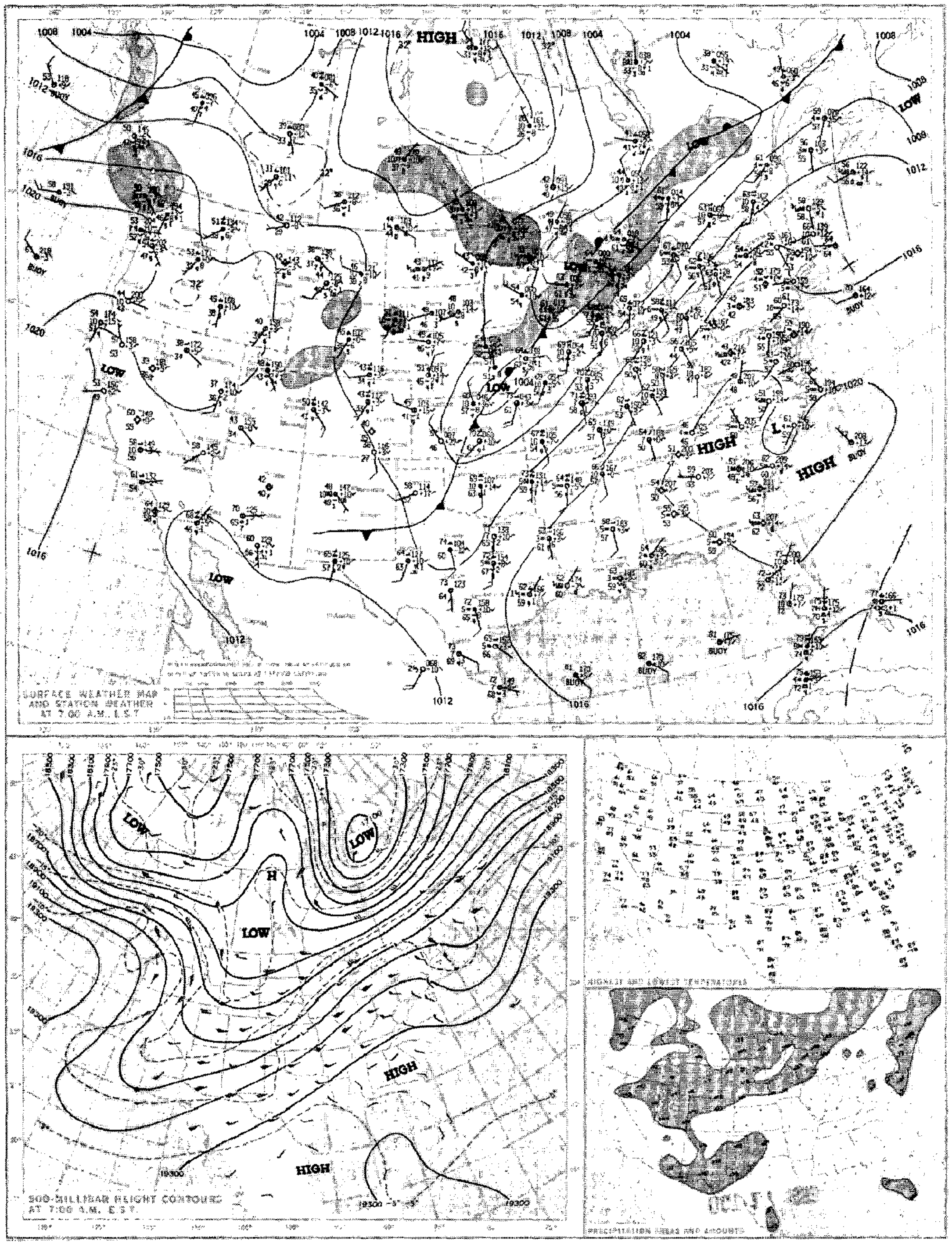
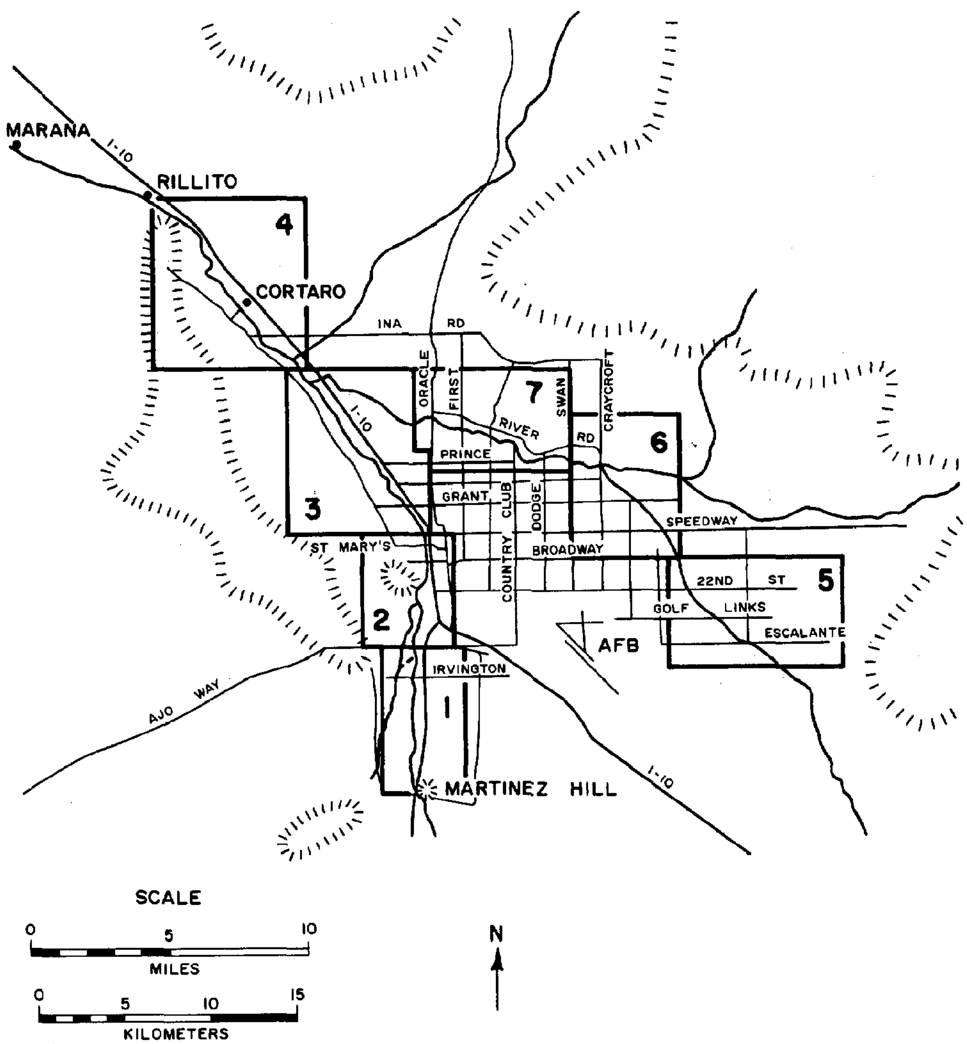


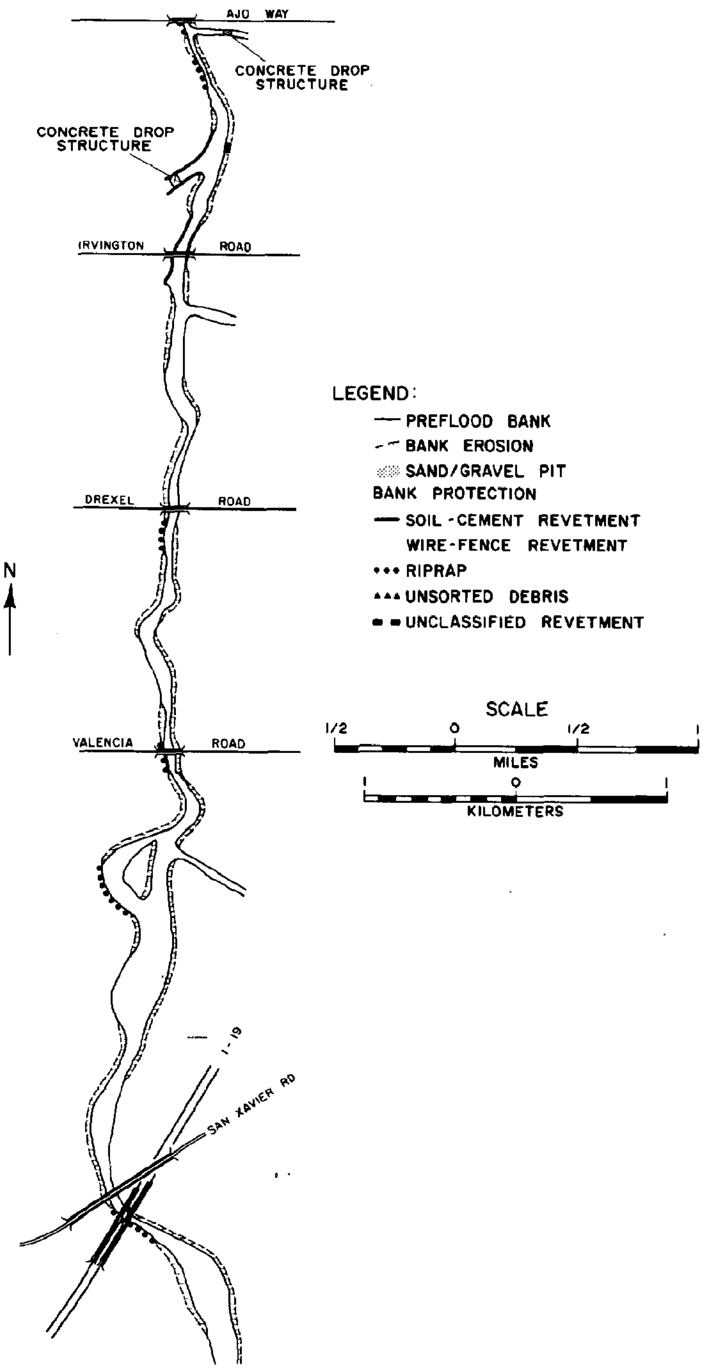
FIGURE A8 Meteorological conditions on Monday, October 3, 1983.

APPENDIX B:

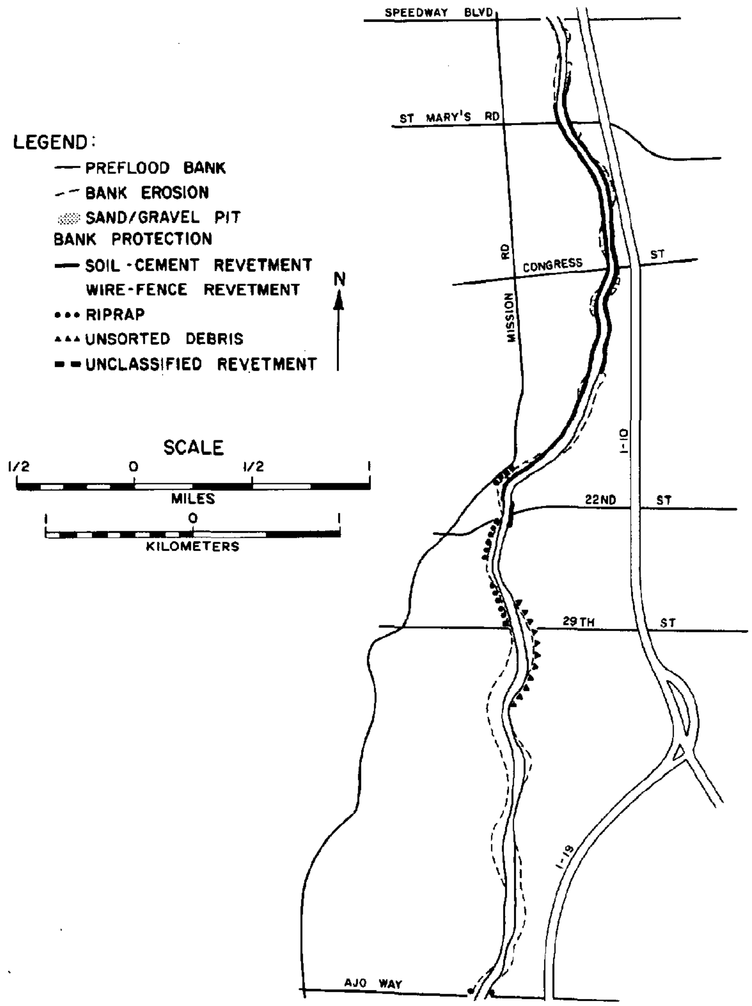
MAPS OF POSTFLOOD BANK EROSION IN THE TUCSON BASIN



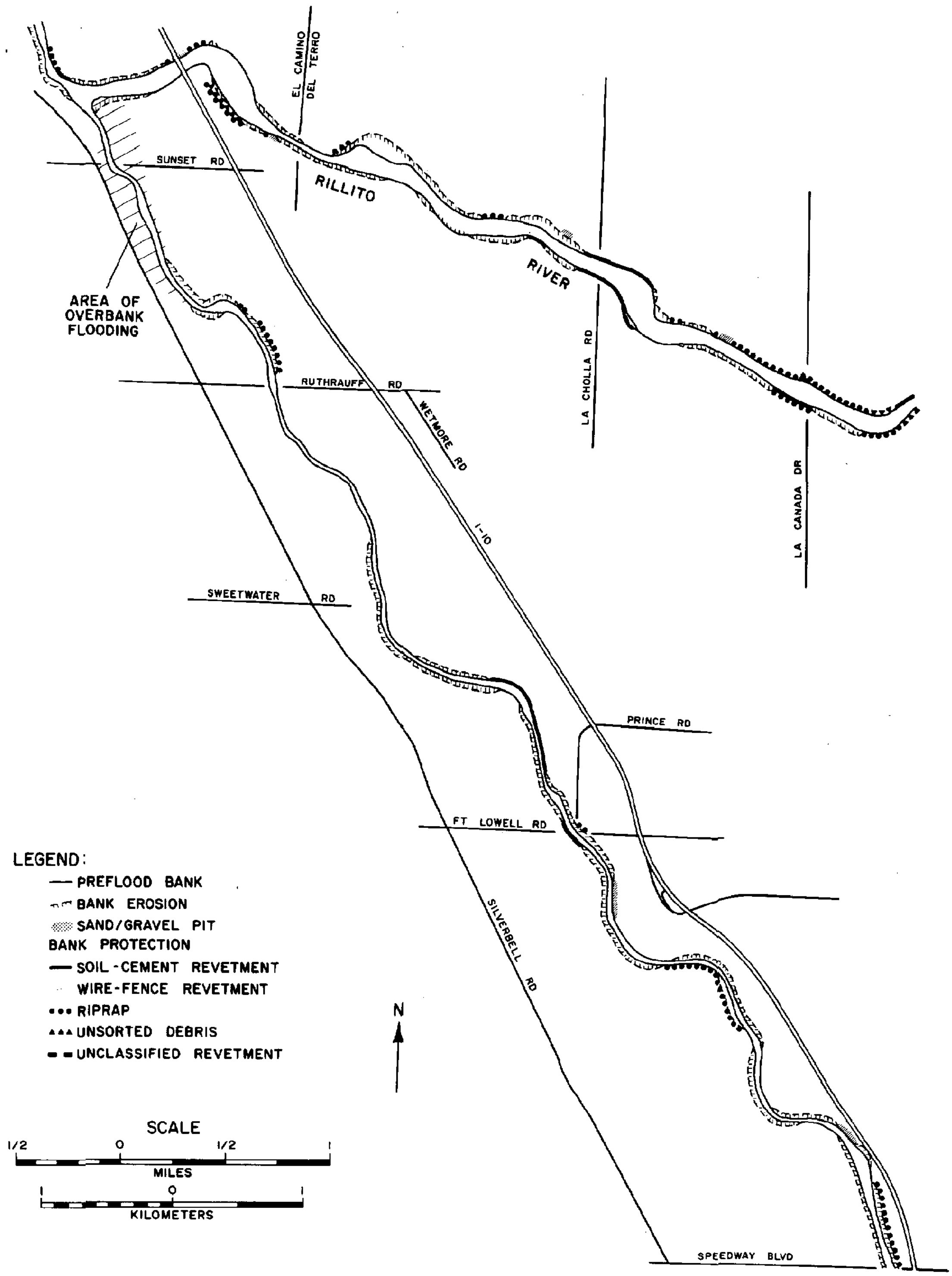
Watercourses near Tucson with an index to the following maps showing erosion, bank protection, and related flood effects from the October 1983 flood.



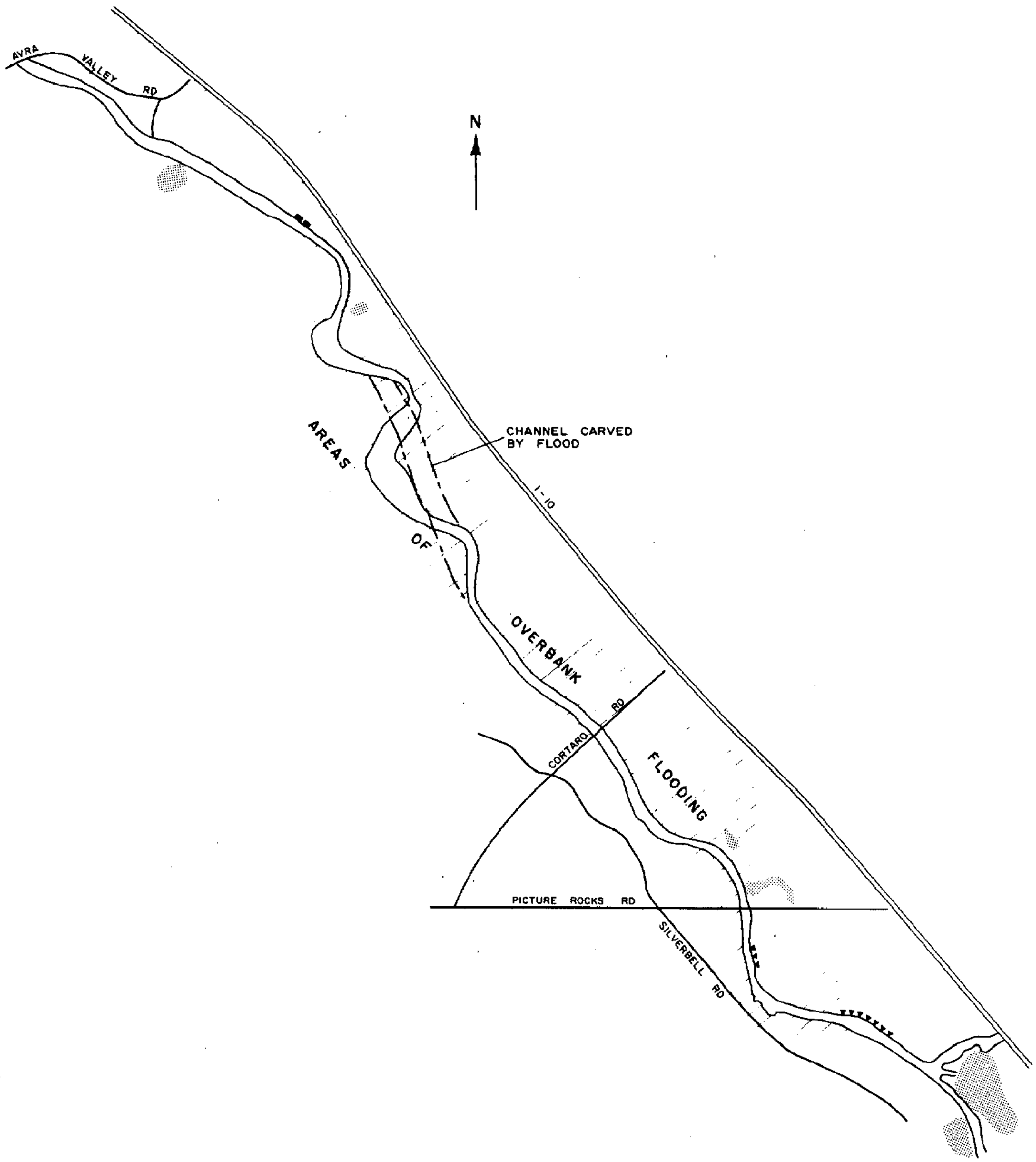
MAP 1 The Santa Cruz River from Martinez Hill to Ajo Way.



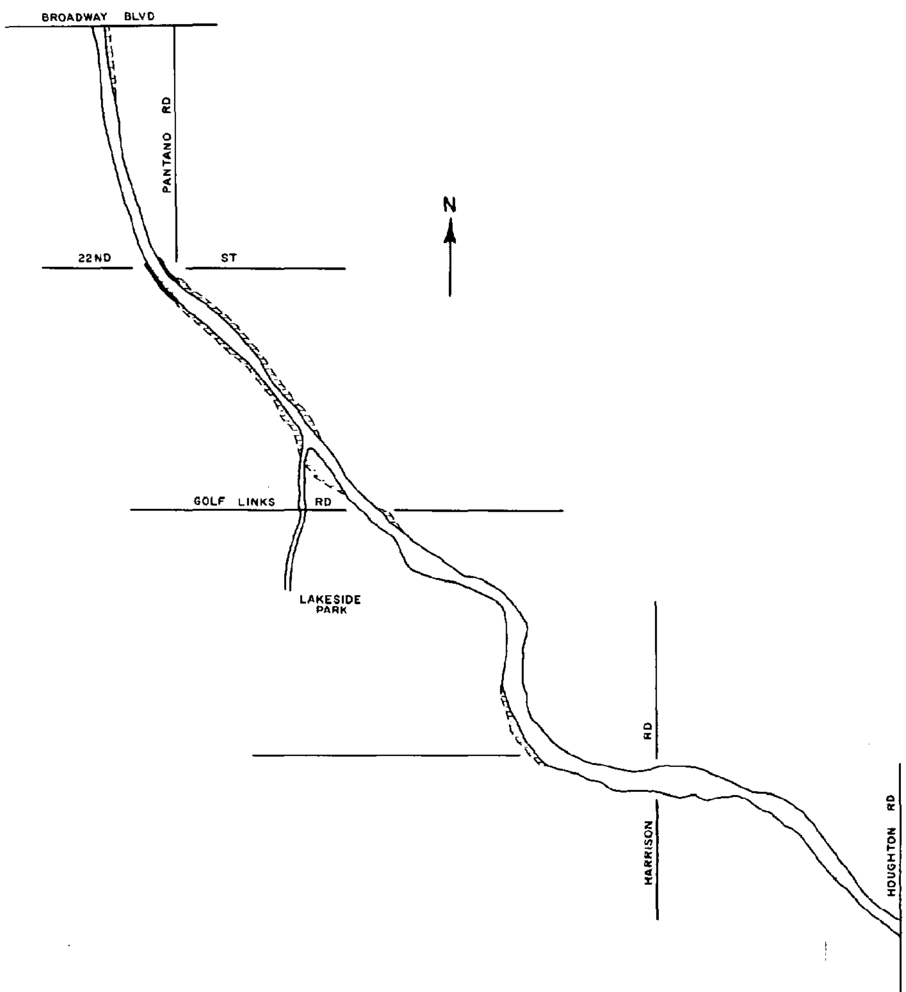
MAP 2 The Santa Cruz River from Ajo Way to Speedway Boulevard.



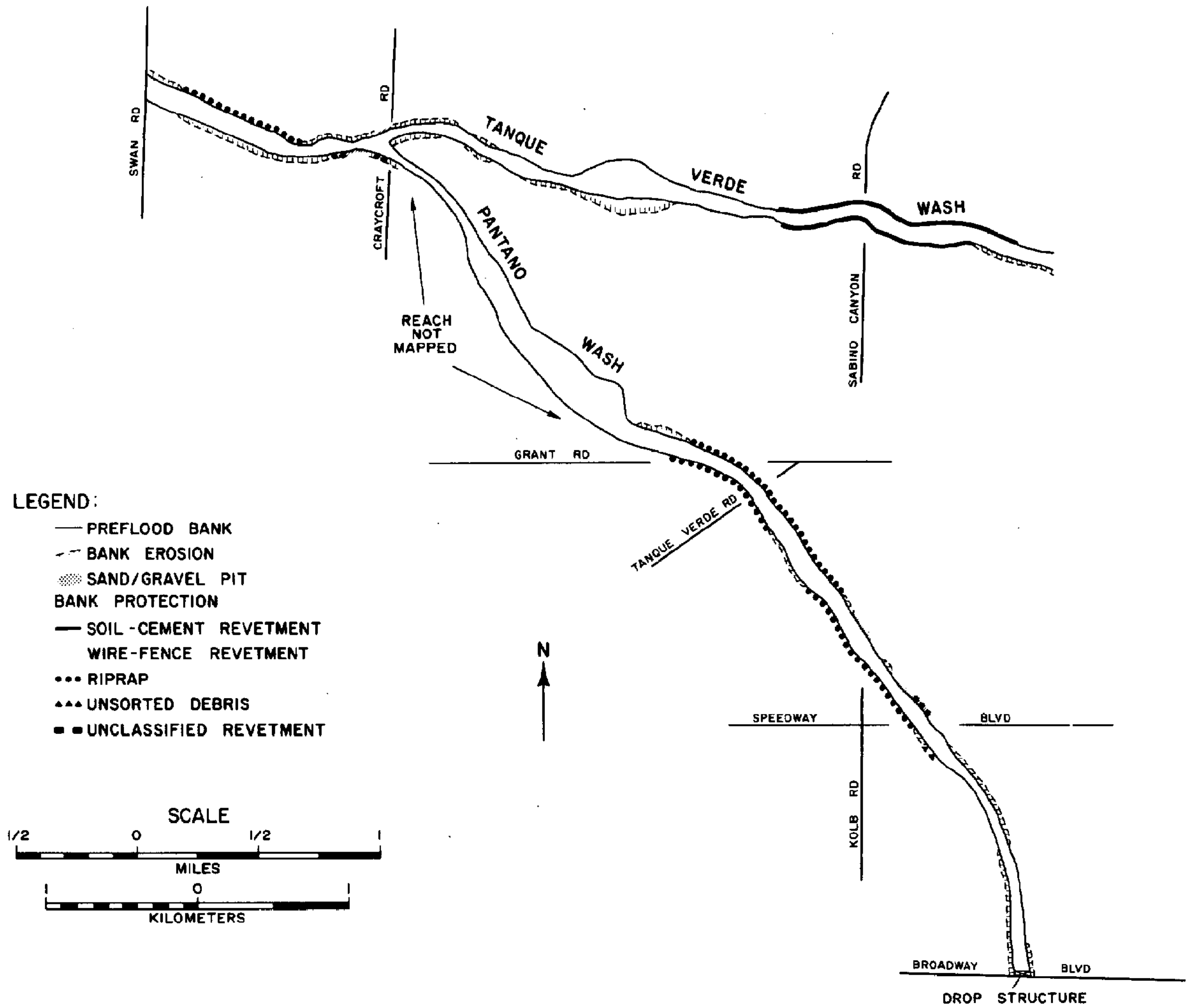
MAP 3 The Santa Cruz River from Speedway Boulevard and the Rillito from La Canada Drive to their confluence.



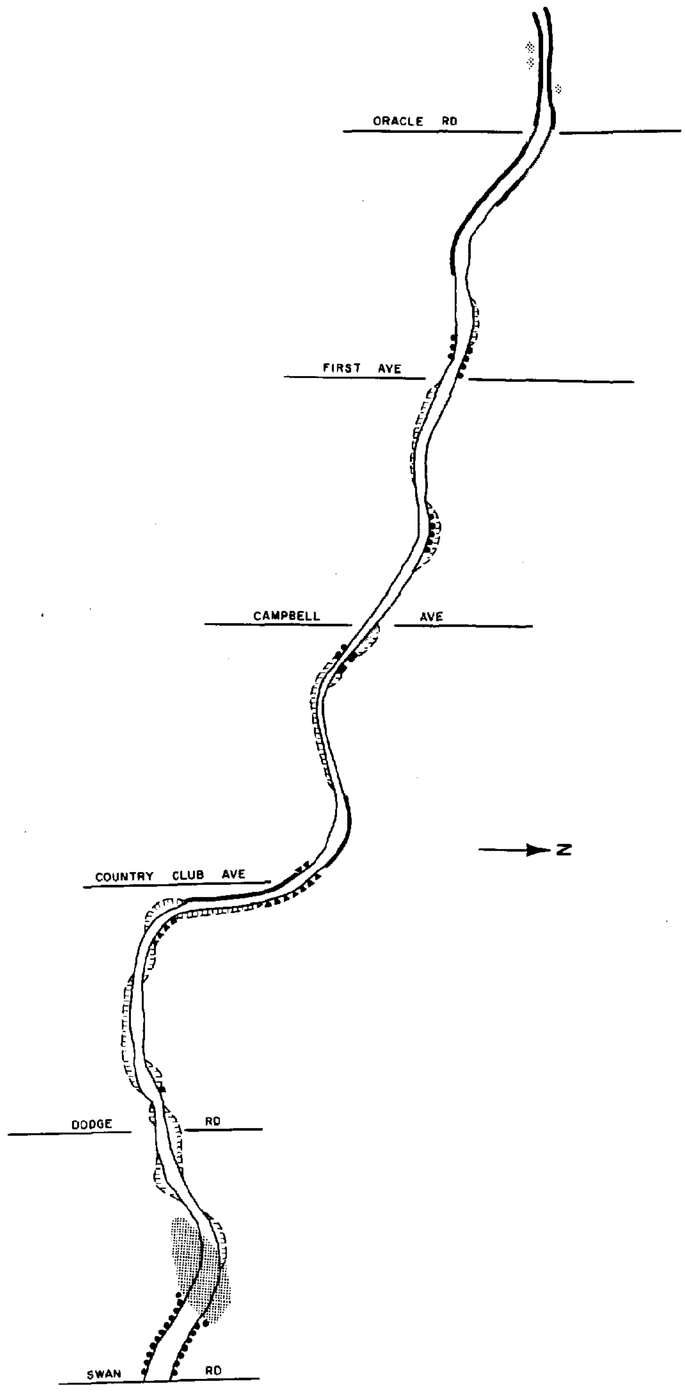
MAP 4 The Santa Cruz River from its confluence with the Rillito to Valley Road.



MAP 5 Pantano Wash from Houghton Road to Broadway Boulevard.



MAP 6 Pantano Wash from Broadway Boulevard and Tanque Verde Creek at their confluence.



MAP 7 The Rillito from Swan Road to Oracle Road.

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Copies available from sources given in footnotes a, b, and c.

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